Department of Architecture

Scalable green infrastructure and the water, vegetation, and soil system

Scaling-up from Finnish domestic gardens

Outi Tahvonen

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 180/2019

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Aalto University publication series
DOCTORAL DISSERTATIONS 180/2019

ISBN 978-952-60-8746-7 (printed)
ISBN 978-952-60-8747-4 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-8747-4

Unigrafia Oy
Helsinki 2019

Finland

NORDIC SWAN ECOLABEL
Printed matter
4041-0619

Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

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Outi Tahvonen

Name of the doctoral dissertation
Scalable green infrastructure and the water, vegetation, and soil system - Scaling-up from Finnish domestic gardens

Publisher School of Arts, Design and Architecture

Unit Department of Architecture

Series Aalto University publication series DOCTORAL DISSERTATIONS 180/2019

Field of research Landscape architecture

Date of the defence 25 October 2019

Language English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract
The 'urban green' concept should be considered in the context of multi-scalar green infrastructure (GI) designed to face the complex challenges of contemporary cities. GI is a spatial network that includes all urban greenspaces and penetrates all land-use categories regardless of their primary function. The main components of urban GI are water, soil and vegetation. Urbanisation and the concomitant increase in impervious surfaces decrease the soil's access to sunlight and precipitation, reducing the potential for site-scale vegetation growth and generating runoff that demands special attention to stormwater management. Impervious coverage defines the extent of soil disconnected form GI. However, water, vegetation, and soil can be integrated as the core system of GI that exists throughout urban landscapes.

This dissertation focuses on the multi-scalar GI of one land-use category, low-density housing (LDH) in Finland. The aims are to study the role of private domestic gardens in LDH as part of the GI and to improve the potential of these gardens to more effectively support city-scale GI. LDH can support GI at city and regional scales as the proportion of non-sealed surfaces is relatively higher than in other urban land uses. However, LDH is typically comprised of many plots, each with a separate owner, making the achievement of this goal difficult with conventional planning tools. The multifunctionality of private gardens in LDH areas was studied via literature review, followed by a two-year experiment in a test field to study the functioning of the GI's core system through the concept of bioretention. An iterative design process to improve the performance of private gardens on the different scales used a variation of the research by design method.

The results provide knowledge for urban planning, garden design and landscape construction that work mainly at different scales of GI. For urban planners the results formulate a check-list to recognize the garden scale multifunctionality in planning process of LDH and criteria for multi-scalar and hierarchical design process for scalable GI. For designers this dissertation proposes improved and integrative design process to functionally combine vegetation and stormwater management at plot scale. For the needs of practical landscape construction in Finland it develops construction details and material specifications of bioretention. The results promote the integration of stormwater management and vegetation and the application of the GI's core system. Designers' knowledge of the core principles allows them to adaptively integrate stormwater management and vegetation with soil throughout the garden space. In addition, the continuous character of the GI's core system relates to the idea of grey and green continuum to provide garden-scale microhabitats and benefit from sealed surfaces for the needs of vegetation. In turn, this garden-based biophysical environment may enhance GI at the block and neighbourhood scales and, thereby, the ecological network of an entire city.

Keywords urban planning, green infrastructure, stormwater, urban vegetation, garden design

ISBN (printed) 978-952-60-8746-7	**ISBN (pdf)** 978-952-60-8747-4
ISSN (printed) 1799-4934	**ISSN (pdf)** 1799-4942
Location of publisher Helsinki	**Location of printing** Helsinki **Year** 2019
Pages 160	**urn** http://urn.fi/URN:ISBN:978-952-60-8747-4

Aalto-yliopisto

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Outi Tahvonen

Väitöskirjan nimi
Skaalautuva vihreä infrastruktuuri ja veden, kasvillisuuden ja maan muodostama systeemi – skaalaus suomalaisista pientalopihoista

Julkaisija Taiteiden ja suunnittelun korkeakoulu

Yksikkö Arkkitehtuurin laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 180/2019

Tutkimusala Maisema-arkkitehtuuri

Väitöspäivä 25.10.2019

Kieli Englanti

☐ **Monografia** ☒ **Artikkeliväitöskirja** ☐ **Esseeväitöskirja**

Tiivistelmä
Kaupunkisuunnittelu joutuu ratkomaan nykyisin moniulotteisia haasteita. Kaupunkivihreän osalta on siirryttävä kaavoitettujen viheralueiden määrittelystä vihreän infrastruktuurin (GI) käyttöön, sillä se toteutuu yhtäaikaisesti useissa eri mittakaavoissa ja koskee siten useita eri toimijoita. GI käsittää viheralueiden muodostaman verkoston lisäksi kaikki eri maankäyttöluokkien vihreät osat. GI:n ydinsysteemi yhdistää maan, veden ja kasvillisuuden. Kaupungistuminen ja siihen liittyvä läpäisemättömien pintojen lisääntyminen vähentävät auringonvalon ja sadeveden pääsyä maaperään. Tämä puolestaan vähentää maavaraisen kaupunkikasvillisuuden määrää ja toisaalta synnyttää tarpeen huleveden hallinnalle.

Tämä väitöskirja keskittyy yhden suomalaisen maankäyttöluokan, pientaloalueen (LDH), vihreään infrastruktuuriin ja sen skaalautuvuuteen. Tavoitteena on ollut tutkia yksityisten pientalopihojen roolia koko asuinalueen GI:ssa ja etsiä keinoja parantaa pientalopihojen merkitystä koko kaupungin kaupunkivihreässä ja siten ekosysteemipalvelujen syntymisessä. Pientaloalueilla on erityinen mahdollisuus tukea kaupunkivihreää ja ekologisten verkostojen yhteyksiä, koska näillä alueilla on muita maankäyttöluokkia enemmän läpäiseviä pintoja. Pientaloalueet muodostuvat kuitenkin lukuisista tontista, joilla jokaisella on eri omistaja ja heillä yksilölliset mieltymykset pihansa suunnittelusta, rakentamisesta ja hoidosta. Tämä väitöskirja tutki yksityisten pientalopihojen monitoiminnallisuutta kirjallisuuskatsauksella ja GI:n ydinsysteemiä biopidätysrakenteita vertailevalla koekentällä. Näiden perusteella tutkimus esittää veden ja kasvillisuuden integroivaa pihasuunnittelumallia, joka kehitettiin soveltamalla Research by Design -menetelmää.

Tulokset ovat hyödynnettävissä kaupunki- ja pihasuunnittelussa sekä viherrakentamisessa. Kaupunkisuunnittelijoille tutkimus on muotoillut tarkistuslistan pihamittakaavan monitoiminnallisuuden tunnistamiseksi ja kriteerit skaalautuvan kaupunkivihreän suunnittelulle. Pihasuunnittelulle tämä väitöskirja ehdottaa kasvillisuuden ja huleveden integroivaa suunnitteluprosessia osana tavanomaista pihasuunnittelua. Lisäksi tulokset tarjoavat suomalaisiin viherrakentamiskäytäntöihin ja -materiaaleihin ehdotuksen biopidätyksen rakenteesta ja materiaaleista.

Skaalautuva GI edellyttää pientalopihoilla aiempaa parempaa kasvillisuuden ja huleveden integrointia sekä koko pihan tarkastelua GI:n ydinsysteemistä käsin. Tonttimittakaavassa tämä edellyttää suunnittelijoilta joustavaa ydinsysteemin tuntemusta ja kykyä sen soveltamiseen. Yksittäisistä pientalopihoista muodostuva alue voi parantaa kaupunkivihreää korttelin ja naapuruston mittakaavoissa ja siten koko kaupungin ekologisessa verkostossa.

Avainsanat kaupunkisuunnittelu, vihreä infrastruktuuri, hulevesi, kaupunkikasvillisuus, pihasuunnittelu

ISBN (painettu) 978-952-60-8746-7 **ISBN (pdf)** 978-952-60-8747-4

ISSN (painettu) 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2019

Sivumäärä 160 **urn** http://urn.fi/URN:ISBN:978-952-60-8747-4

Acknowledgements

It took me almost eight years to complete this dissertation. Occasionally, progress on this dissertation resulted from te devotion of my full attention, but to a large extent, it took place in the background of my work as a lecturer at HAMK. While the time span seems to been long—and may have been unnecessarily long in terms of national educational policy lines—it has allowed for careful maturation of the theme. That maturation took place through conversations with my colleagues and students during my normal daytime work in Lepaa, postgraduate courses and guidance discussions in Otaniemi, and occasional and completely unpredictable encounters in everyday life. These encounters were numerous, and I do appreciate each of them. In the following, I will try to highlight some of the persons and events that have contributed most to the different phases of my research.

For me, the most important initial impetus for starting my dissertation research was the participation in the ECLAS conferences, where I realized the multidisciplinary research of landscapes to be something tangible and also pragmatically implemented work. In this context, discussions at Doctoral Colloquium organized by Simon Bell and Ellen Fetzer have been a great help in designing my research and developing its relevance. At the same time, internationality became more concrete during my courses at HAMK, where I taught international and Finnish students. These courses formed the background to combine European research needs in landscape architecture with my personal interests in stormwater management, green infrastructure, and garden design. The lack of knowledge in stormwater management has already been revealed in my guide-book with Reijo Eskola, and I had concentrated on the urban green in my environmental science graduation at the University of Helsinki. I was motivated to study these topics by my years of experience in practical garden design.

The content of my research was further defined in discussions with Jyrki Sinkkilä and Miimu Airaksinen in the application phase for postgraduate studies. Subsequently, the research plan was refined in all post-graduate courses, led by Kimmo Lapintie, Hossam Hewidy, Antti Ahlava, Mina di Marino, and Jyrki Sinkkilä. In the second half of my doctoral studies, Juanjo Galan, who has been the supervisor of my work, joined the project. He jumped in after some of the articles had already been written, but he greatly influenced the approach, structure, and editing of the compiling part. Simon Bell and Tapio Katko, the latter of whom has also accepted the role of the opponent, have been pre-examiners of the resulting entity. Thanks to all of you for supporting my academic thinking.

Although writing an article dissertation is just writing articles, it took me a while to find the writing practices. I gained real insight into scientific writing during two special encounters. The first insight came from an intensive course led by Tim Richardson on scientific writing on landscape architecture at the Latvia University of Agriculture. A week-long workshop course opened my eyes to writing as work—that is, just work. The production of scientific writing in turn opened up with Raine Mäntysalo's persistent and constructive personal assistance in the process of writing the first article. Thank you both for helping me to understand what scientific writing really is.

My research also included field tests and the construction of the actual test field. They required both fundraising and the sympathy of my home organization. Drowning tests required torture of plants, regular care and construction of basic infrastructure. The construction of the test field required earthwork, installation of drainage systems, mixing of soil, development of data service, planting, rinsing, covering, filming, simulating heavy rain, and endless shoveling. Thanks to Heikki Peltoniemi for allowing and enabling this work, Rikala Foundation for financing, and for Kaija Suominen, Salla Leppäkoski, Teuvo Räsänen, Tommi Syrjälä, Teemu Lainesalo, Kati Vesala, Anne Asumaniemi, Ilona Rantola, and Antti Mäkelä for doing the work. Thank you for helping me to carry out my research.

Research is not always straightforward formulations, analysis, or publication. Brainstorming and just thinking require space and reflection. I've been fortunate to meet like-minded doctoral students; together, we set up a research group concentrating on green infrastructure (VirMa). VirMa allowed me to reflect on and develop my own thinking and test my precious thoughts in the most supportive and constructive atmosphere. Thank you, Elisa, Mari and Elina for your peer support, which has clearly been invaluable.

I have received sincere support and firm faith while completing this dissertation from friends, relatives, and family, especially in those difficult moments when I despaired that I would never be able to finish this project. While I worked on this dissertation, my daughters grew from young children into teens, my husband became middle-aged, and our house loan was significantly reduced. Thank you for being with me during this period of my life.

Looking forward to the future and post-doctoral projects,

Vantaa, 19 September 2019
Outi

Contents

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

1. Tahvonen, Outi; Airaksinen, Miimu. 2018. Low Density Housing in Sustainable Urban Planning – Scaling down to private gardens by using the green infrastructure concept. Land Use Policy, 75, 478-485.

2. Tahvonen, Outi. 2018. Impervious Coverage in Finnish Single-Family House Plots. Potential of low-density residential areas in stormwater management and creating urban green spaces. Architectural Research in Finland, 2, 180-194.

3. Tahvonen, Outi. 2014. Water for Vegetation – Knowledge Base for an Integrated Approach to Sustainable Stormwater Management in Site scale. Eclas2014 Conference, Landscape: A Place for Cultivation. Porto, Portugal, 2014, pp. 331-333.

4. Tahvonen, Outi. & Riihimäki, Mona-Anitta. 2016. Urban Vegetation for Bioretention in Cold Climate – A Short Interval Flooding Test in Finland. Eclas2016 Conference, Bridging the gap, Rapperswil, Switzerland, pp. 497-500.

5. Tahvonen, Outi. 2018. Adapting Bioretention Construction Details to Local Practices in Finland. Sustainability, 10, 276. (17 p.)

6. Tahvonen, Outi. 2018. Scalable Green Infrastructure - the Case of Domestic Private Gardens in Vuores, Finland. Sustainability, 10, 4571. (16 p.)

Author's Contribution

Publication 1: Low Density Housing in Sustainable Urban Planning – Scaling down to private gardens by using the green infrastructure concept

I developed the idea, research design and report. Professor Miimu Airaksinen guided the overall structure and collaborated in writing the discussion.

Publication 2: Impervious Coverage in Finnish Single-Family House Plots. Potential of low-density residential areas in stormwater management and creating urban green spaces

I am the sole author for this paper.

Publication 3: Water for Vegetation – Knowledge Base for an Integrated Approach to Sustainable Stormwater Management in Site scale

I am the sole author for this conference paper.

Publication 4: Urban Vegetation for Bioretention in Cold Climate – A Short Interval Flooding Test in Finland

I developed the idea for this study. We developed the research design together with Mona-Anitta Riihimäki. I was organizing the practical implementation for the study including data collection, analyzing and reporting. Mona-Anitta Riihimäki guided the overall structure and collaborated in writing the paper.

Publication 5: Adapting Bioretention Construction Details to Local Practices in Finland

I am the sole author for this paper.

Publication 6: Scalable Green Infrastructure - the Case of Domestic Private Gardens in Vuores, Finland

I am the sole author for this paper.

List of Abbreviations

CS	Core system (of green infrastructure)
ESS	Ecosystem services
GF	Green factor
GI	Green infrastructure
LDH	Low density housing
NBS	Nature based solutions
OM	Organic matter
PMC	Patch-matrix-corridor
RbD	Research by Design
SES	Socioecological systems
SWM	Stormwater management
SUDS	Sustainable urban drainage system

1. Introduction

The world's population and the proportion of urban inhabitants continue to increase. Globally, the share of urban population has increased from 30% to 55% in less than 50 years, and this tendency is expected to continue and to reach the proportion of 70% by 2050 (United Nations, 2018). The growth of cities occupies land from agricultural fields and forests causing soil sealing and, therefore, multiple challenges such as urban stormwater management, biodiversity loss, and micro-climatig changes as urban heat island effects.

The growth of cities and towns requires finding a balance between ecological, economic, and social pillars of sustainable development. Urban planning frames the growth strategy by expanding or densifying urban areas in order to provide healthy and comfortable living conditions for residents. Generally, urban densification reduces the proportion of soil-connected greenspaces in urban areas, but on the other hand, urban sprawl expands the overall urban coverage. The achievement of a balance between these two diverging trends challenges urban planning to reconsider the different land use categories used in conventional zoning and to support the urban green embedded in the grey.

The overall urban green is a city-specific combination of ecological networks, urban vegetation, wastelands, single street trees, and flowerbeds. This multiscalar concept has changed along scales and specific objectives, but lately the use of green infrastructure (GI) has been established. Green infrastructure is thought to play an essential role in residents health and well-being (Tzoulas et al., 2007). It is used for aesthetic and technical purposes and plays a keyrole in climate change adaptation (Gill, Handley, Ennos, & Pauleit, 2007). The GI concept can produce scalable, multifunctional, connective, and resilient green spaces and address both water and vegetation (Abunnasr, 2013; Benedict & McMahon, 2001; Mell, 2010).

An increase in impervious coverage is an inevitable outcome of urbanisation as the proportion of roofs, streets, and parking increases (Arnold & Gibbons, 1996; Miller et al., 2014). This change in surface coverage obstructs water infiltration which affects the quality and quantity of runoff, and destroys the connection between vegetation and the subsoil, along with its seed bank, water, and nutrient reservoir. This urban context also defines the spatial and growing conditions for urban vegetation.

The challenge of increased runoff has directed attention to stormwater management to prevent urban flooding and to improve receiving water quality. Sustainable urban drainage systems (SUDSs) provide a set of methods to manage runoff locally (Kellagher et al., 2007). However, stormwater management strategies have tended to focus on improving water quality and decreasing water quantity as imperviousness prevents infiltration and generates runoff. Because SUDSs primarily address stormwater management, they did not initially focus on vegetation coverage or plants' active role in the local water cycle.

Although vegetation and its growth depend on water availability, the connection between vegetation and its water supply may be lost in site-scale designs if stormwater management mainly concentrates on efficient water quantity management. In a built environment, plants may grow in small soil volumes surrounded by coarse gravel and subsurface drainage; rainwater runs along concrete gutters, preventing infiltration from reaching these plants. The integration of water and vegetation needs to be improved so that the solutions for stormwater management achieve better multifunctionality on the site scale and prepare for changes in precipitation patterns.

The basis for integrating water and vegetation is framed by the zoning process and by the characterisation of different land-use categories in traditional planning. It is noted that neglectful densification and infill reduce the proportion of green spaces in private gardens and public parks. This has prompted planners to develop new ideas for overall city-scale green space provisioning that builds on the essential core components of GI: water, soil, and vegetation. The share of private greenspaces in the urban green network can provide private and public benefits and become a valuable component of a diverse, rich urban GI that builds resilience in compact cities.

Sustainable urban planning would benefit from the development of scalable tools for planning and managing the city-scale proportion of pervious surfaces and vegetation coverage, which would also serve as site-scale guidelines for incorporating the degree of multifunctionality required in dense cities. To provide vegetation-integrated stormwater management and multifunctionality, a more integrative approach to site-scale design should be developed rather than continuing to utilise separate tools for stormwater management and vegetation provisioning.

The low-density housing (LDH) land-use category makes balancing between housing density (and control over urban sprawl) and the impervious coverage it causes, as well as the proportion of urban green space it provides, more challenging. Housing density frames the proportion of imperviousness, and ongoing changes in gardening trends modify plot-scale landscaping.

Low-density housing is a relevant urban land-use type in urban fabric and there is a continuous demand for it. Three quarters of the population in EU-28 countries live in urban areas and over half of Europe's population live in detached, semi-detached or terraced dwellings. Low density urban patterns are perceived to have an impact on sustainability and climate change as a consequence of the higher demand of energy and resource per capita and the increased pressures on local ecosystems and biodiversity (Urban Europe, 2016).

Urban sprawl rate in Finland is comparable to other European countries as it is slightly above the average among other European countries (European Environment Agency, 2017). However, each of the EU Member states has faced distictive history of territorial developments (Urban Europe, 2016) In Finland, for example 40% of household dwellers in Espoo, second largest city in country currently live in single-family houses or rowhouses. However, extensive use of LDH can increase the coverage of urban areas and cause urban sprawl. Therefore, sustainable urban planning needs to recognise both the positive potential of LDH and its limitations or shortcomings. Low-density housing and its private gardens can provide ecosystem-based services and benefits for residents, such as support for biodiversity and ecological networks, the capacity to manage stormwater, a proportion of urban vegetation for the whole city and well-being for individual plot owners.

The focus, here, is on private gardens as part of urban green space networks and, more specifically, their role in GI as an essential component of urban sustainability. Impervious coverage defines the surface area for ground-connected processes that infiltrate water and support vegetation growth. When these processes function adequately, they provide ecosystem services for the residents. In turn, residents may foster these processes via their gardening activities and, therefore, strengthen the socioecological system (SES) dimension of LDH. This study aims to enhance urban GI by producing new knowledge the case of LDH using a scalable approach in the Finnish context. It begins with private gardens in LDH, develops detailed plans for integrating water, vegetation, and soil through a prototypical study of bioretention, and then scales up to blocks and neighbourhoods.

1.1 Aims and research questions

The overarching aim of the thesis is to research the role of private gardens in urban GI and develop their potential to better support the city-scale green space system through the practices of sustainable urban planning and design. This dissertation has three aims, which form a scalable continuum. The first aim, which relates to the plot scale and its gardens, is to map the current situation, both as functions and as surface coverage. This initial scale is assumed to be the core of GI in LDH housing areas, and the aim is formulated as follows:

> *AIM A: To present the state-of-the-art of private domestic gardens for green infrastructure.*

This first aim implies defining the existing role of domestic private gardens and their characteristics for GI within the framework of sustainable urban planning. To address this aim, private plots and their associated gardens are grouped into functional units called LDH areas. Two research questions (RQ) address the first aim:

> *RQ 1: What is the role of private domestic gardens in green infrastructure within the framework of sustainability?*
> *RQ 2: How is the non-sealed area of Finnish domestic gardens generated on the plot scale?*

While RQ1 concentrates on the general features of private plots in LDH and their role in urban green space networks and systems, RQ2 clarifies how the planning and design process frames possibilities for non-sealed surfaces and, therefore, the potential for ground-connected GI on the plot scale. Urbanisation and the increasing proportion of impervious coverage seal the surface, preventing rainwater infiltration and hindering vegetation's connection to the subsoil. Generally, urban imperviousness is related to a reduction in total green space coverage (Fuller & Gaston, 2009). In this study, the starting point is the outcome of the spatial planning process, which provides a framework for a combination of plot-scale decisions, guidelines, and regulations. In practice, this regulatory system enables or restricts imperviousness and, therefore, defines the general possibilities for ground-connected vegetation coverage in these areas. Aim A, therefore, explores plot-scale potential and practices for mapping the state-of-the-art of private gardens for further development. Figure 1 presents all three aims in the context of this study's main focus: scalable GI through upscaling from private gardens.

The second aim, AIM B, addresses challenges for the practical implementation of sustainable garden design practices. The second aim is to concentrates on detailed, thorough development of construction details and plant selection based on local conditions and stormwater management. The aim is stated as follows:

> *AIM B: To develop detail-scale integration between water and vegetation for local conditions.*

The use of vegetation in stormwater management is not a self-evident choice for every designer or for every site, and it does not need to be. Some sites require practices that prevent infiltration or locate infiltration beyond the reach of root systems. However, well-drained urban environments, by nature, produce dry growing conditions, and drought is one of the main factors limiting the growth of urban vegetation. Regarding sustainable cities and the role of urban green spaces, it is paramount to achieve a higher level of integration between vegetation and (rain) water, which is addressed by GI. Bioretention is a stormwater management practice that combines water, vegetation, and soil and emulates several natural processes in the water cycle, such as infiltration, filtration, evaporation, and storage, both in ponding areas and in soil. Vegetation plays an active role in these processes, and, as bioretention is applicable to several conditions and locations within built environments, it provides relevant information for the development of detail-scale integration between water, vegetation, and soil. The research was conducted in Southern Finland; therefore, the study applies to cold climate conditions in the Nordic context. The associated research questions for AIM B are as follows:

> *RQ 3: How should the interaction between soil, water, and vegetation be optimised in Finnish private gardens?*
>
> *a) How should this interaction in the form of bioretention be adopted in local practices?*
>
> *b) What are the construction details and criteria for plant selection?*

The third aim, AIM C, is to improve design practices in gardens to better support overall GI on the block and neighbourhood scales in LDH. This improvement is developed from the results of addressing AIM A and AIM B.It entails evaluation of the integration of water, soil, and vegetation on the platform of LDH. The third aim is stated as follows:

> *AIM C: To improve garden-scale GI to enhance up-scaled GI.*

The concept of sustainability and the idea of compact cities returns, here, to the role of the framework. The purpose is to examine how vegetation-integrated stormwater management in garden design and management can support plot-scale design choices and a more systemic contribution on larger scales. The associated research question is stated as follows:

> *RQ 4: How can plot-scale GI be improved to enhance GI at the block and neighbourhood scales?*

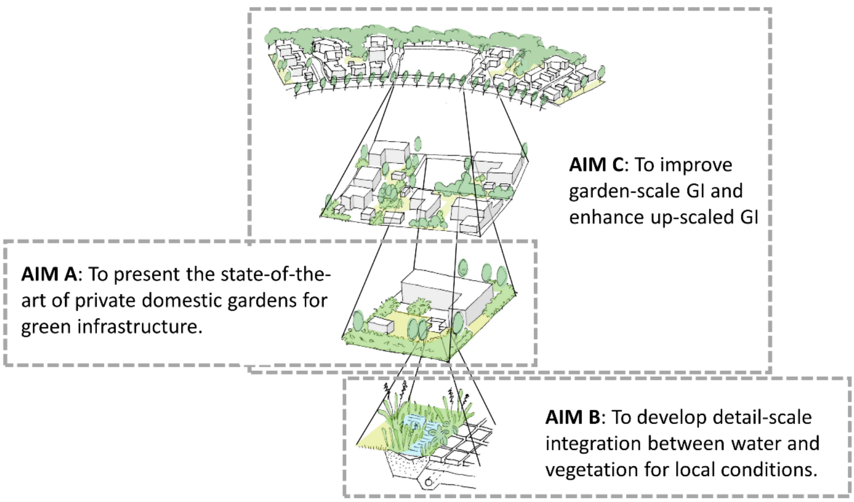

Figure 1. Research aims related to the context of this dissertation. (Figure, O.Tahvonen)

Research aims are presented in Figure 1 and Table 1 summarises the research questions and their relationship to the research aims.

Table 1. Summary of aims and research questions.

Aims	Research questions
AIM A: To present the state-of-the-art of private domestic gardens for green infrastructure	RQ 1: What is the role of private domestic gardens in green infrastructure within the framework of sustainability? RQ 2: How is the non-sealed area of Finnish domestic gardens generated on the plot scale?
AIM B: To develop detail-scale integration between water and vegetation for local conditions	RQ 3: How should the interaction between soil, water, and vegetation be optimised in Finnish private gardens? a) How should this interaction in the form of bioretention be adopted in local practices? b) What are the construction details and criteria for plant selection?
AIM C: To improve garden-scale GI to enhance up-scaled GI	RQ 4: How can plot-scale GI be improved to enhance GI on the block and neighbourhood scales?

1.2 Research process and dissertation structure

This dissertation consists of four peer reviewed journal papers and two peer reviewed conference proceedings, which form a solid base for the whole study. A single paper may address several aims simultaneously or link the different scales more closely. (Figure 2). The list of papers with full bibliographic information is presented at the beginning of this dissertation.

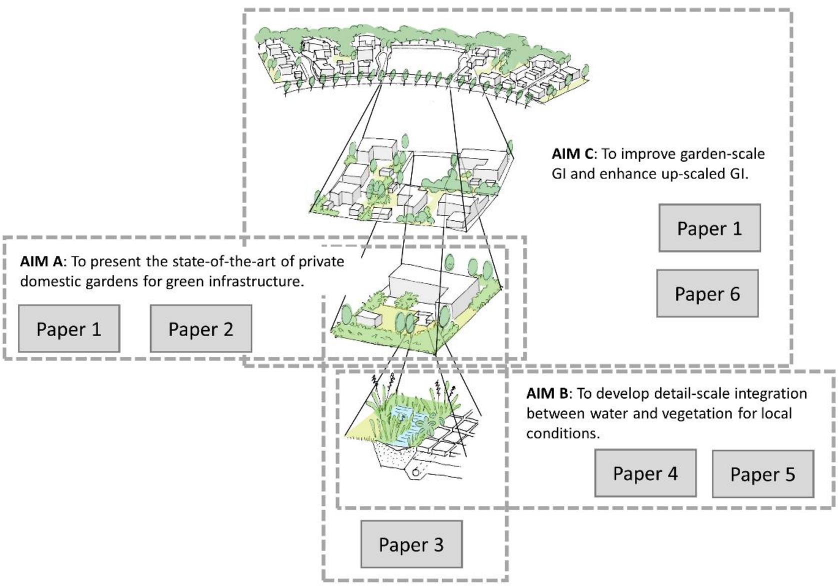

Figure 2. The set of papers and their schematic interrelations.(Figure, O.Tahvonen)

Like many other studies, this dissertation has evolved over time. Initially, the main focus was on urban densification and a desire to identify the limits of densification that allow GI to function on the plot scale. Along the way, the focus shifted to the potential of private gardens as the need for this preliminary knowledge presented itself.

The research was completed in three phases: (a) obtaining knowledge of current private domestic garden practices (Papers 1, 2 and 3), (b) conducting outdoor experiments on plants and construction practices (Papers 4 and 5), and (c) developing garden-scale GI to enhance city-scale GI (Papers 1 and 6). The first phase entailed the current situation on the plot scale. This scale was the starting point, and the research began with a review of journal articles addressing plot-scale elements and functions, enhanced by a study of impervious coverage in Finnish gardens. This first paper (Paper 1) took several years to be completed and published (Figure 3).

During the early stage, the methodological aim was to construct an experiment involving a vegetation-integrated stormwater construction site to provide practical guidelines for garden design and professional landscape construction. The field experiment was designed, and funding was applied for at the beginning of the study. However, it took several years to begin conducting the field experiments. Several applications were submitted to obtain funding to constructing the test field. Undoubtedly, it was, and still is, the most extensive investment in this research.

The experimental phase produced two papers (Papers 4 and 5) over a two-year period and included a pre-study to estimate suitable vegetation and appropriate growth media, followed by the development and implementation of a test field. These activities involved several staff members from Häme University of Applied Sciences and private land builders. Therefore, the construction work and data collection proceeded rather quickly. The idea for Papers 2 and 3 was developed at the early stages of this research project, although Paper 2 was finalised after the field experiments.

The aim of the final phase was to assess the up-scaling possibilities using the acquired knowledge to add new scales to the conducted research. The final article combines all the previous studies into a very practical approach to design and planning practices at the block and neighbourhood scales. It utilises the researcher's background as a garden designer and integrates practical skills with the knowledge gained from previous articles and with a system-based approach to private gardens in LDH areas.

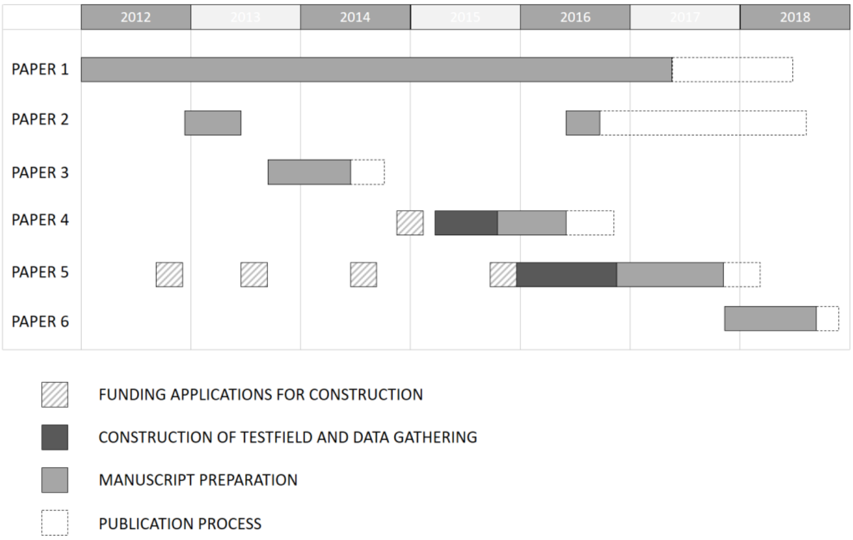

Figure 3. Timeline of the study's funding applications, fieldwork, and publishing process.

This dissertation consists of five chapters. The first chapter describes the approach to the topic and the structure of the dissertation and formulates the present research aims and questions. The second chapter presents the theoretical framework for garden-based and scalable GI and describes the role of water, soil, and vegetation within gardens and GI in LDH areas. This theoretical part first explores the key concepts in urban and green area planning and presents the core system of GI and its components: water, soil, and vegetation. Lastly, it frames up-scaling and the possibilities for scalable GI in LDH.

Chapter 3 describes the research strategies and methods used in this dissertation. These strategies and methods are related to the diversity of methods used in landscape architecture. The main findings of the published papers are summarised in Chapter 4 in accordance with the three overall aims of this dissertation. First, the existing situation of private gardens in the literature and in the Finnish context is described. Then the results of the development of vegetation-integrated stormwater management using bioretention as a prototypical and highly controllable case are presented. Lastly, the results of the development of garden-scale design to enhance up-scaled GI are reported. Chapter 5 discusses the practical and scientific impacts of this dissertation, assesses the reliability and validity of the dissertation, and presents recommendations for further research.

2. Theoretical framework

This chapter begins by positioning the dissertation within a conceptual context. This is followed by a description of the concept of GI and its principles focusing on the proposed GI's core system, which involves water, vegetation, and soil. The chapter concludes with the selection of one land-use category, LDH, in the context of scalable GI. The role of private gardens is described in the overall urban context and as part of the overall urban GI.

2.1 Conceptual positioning of the study

2.1.1 Biophysical and spatial concepts

Urban vegetation and green areas involve numerous overlapping concepts. These concepts have developed on the base of different paradigms, practices, and goals. Although different definitions for the same concepts might create confusion across disciplines, it also shows the importance of urban green spaces. Here, the urban green concept stands for a holistic, multi-scalar biophysical entity that penetrates all land-use categories regardless of ownership. It includes protected and unprotected, as well as planned and unplanned areas, and incorporates natural and man-made green spaces. Furthermore, the urban green concept corresponds to the Finnish word '*kaupunkivihreä*', which generally means all vegetation in the urban context.

Urban green includes both public and private green areas (Figure 4). Municipal approaches utilised in park management departments usually address planned green areas, such as public parks and cemeteries. These areas are defined during the processes of urban planning and zoning, which produce master plans. Within these master plans, the components, which are publicly-owned form a 'green area network' (*viheralueverkosto* in Finnish). City planners design this network to serve citizens and to be accessible to local residents (Ympäristökeskuksen, n.d.). Having being established, these public green areas may be developed by strategic 'green area programmes' (*viheralueohjelma*) through collaboration between municipalities and residents (Sipilä, Bäcklund, & Tyrväinen, 2009).

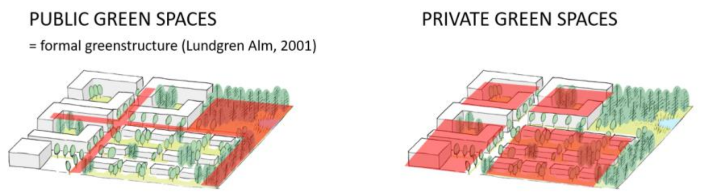

Figure 4. The components of public and private green in the overall urban green. Public green areas consist of parks, street vegetation, and cemeteries, whereas private ones consist of residential, commercial, and business areas. The division of public and private proportions of the urban green forms a backbone for other concepts. (Figure, O.Tahvonen)

During the planning process, the urban greenspaces are considered greenstructure or GI. Green infrastructure as a named concept originated in the United States (US), whereas greenstructure as a concept was used more frequently in Europe, especially in the Netherlands and the Nordic countries (Tjallingii, 2005). Both concepts may include the privately owned component of urban green spaces.

The concept of greenstructure has evolved to resonate with urban structure. Therefore, it aims to stress the value of the green component compared to the grey component in zoning practices. This distinction is emphasised by the concepts of actual and formal greenstructure (Lundgren Alm, 2001, 2007). A formal greenstructure contains only public green areas presented in master plans, but actual greenstructure includes all types of greenspaces and natural elements, such as streets, private plots, and wasteland. The *Action C11* report from European Cooperation in Science and Technology (COST) states that while greenstructure is not a familiar term in every country, the concept is based on the idea of providing a network of green elements that offers more than a network of public green areas (Tjallingii, 2005). Lundgren Alm (Lundgren Alm, 2001) merges functions based on ecological, social, cultural, economic, and technical dimensions within the framework of greenstructure, which resonates with the increasingly used concept of ecosystem services.

The definition and content of the concept are crucial for managing and identifying the participants and benefits as these affect the overall urban green. Therefore, LDH and private gardens or wastelands awaiting development are difficult to manage as a part of the formal greenstructure, and these areas may remain excluded from presentations of greenstructure (e.g. Kaupunkisuunnitteluvirasto 2014).

Recently, greenstructure seem to have been accepted in urban planning as an actual greenstructure that includes both private and public areas. However, there remains some confusion with regard to practical construction sites, especially in Finnish, because the term greenstructure (*viherrakenne*) applies to landscape construction details when defining green roofs, facades, or other vegetation-related details. This confusion reveals the need for a multi-scalar concept that fits both the planning scale and the detailed scale. To meet this need, the concept of GI is one possibility as it is both practical and scalable. Ely and Pitman (2014) describe three approaches: (1) GI as a platform for ecosystem services, (2) GI as connective linkages, analogous to conventional engineered networks, and (3) GI as a tool for specialised green engineering, concentrating on measures such as green roofs, living walls, and bioretention as ways to purify surface runoff. If GI is considered to contain all the green in a city, regardless of ownership and intended land use, it corresponds to the concept of an actual greenstructure (Figure 5).

Figure 5. The concepts of actual greenstructure and green infrastructure encompass an idea of the overall green in the city. These approaches may ignore the ownership or planned use of an area when considering the content of the urban green. (Figure, O.Tahvonen)

Definitions of GI are numerous and still evolving. Traditionally, GI at the regional scale referred to areas of land that are least affected by human actions, but the expanded definition includes areas that are engineered to mimic natural processes and provide cost-effective ecosystem services (Abunnasr, 2013). This general description of the concept is supported by Mell (2008), who defines GI as having both conservation and resource management purposes, as well as a multifunctional nature that connects people with the environment and provides multi-scalar benefits for residents. The European Commission (European Commission, 2013) subsequently used this two-fold definition of GI, referring to it as a strategically planned network of natural and semi-natural areas and stressing its two-fold character as both a strategy to enhance natural capital and a successful, tested tool for providing ecological, economic, and social benefits through natural solutions. These definitions extend the strategic approach of landscape conservation to man-made environments under the concept of GI, which, in turn, supports the use of GI to cover all the greenspaces in urban areas.

Recent definitions of GI have generally incorporated these two main approaches. The US Environmental Protection Agency (EPA, 2014) defines GI as a system that uses natural or engineered systems to mimic natural processes, enhance overall environmental quality, and provide utility services. Natural England (*Green Infrastructure Guidance*, 2009) reduces the definition even further to a planned network of living systems affecting the quality of life in urban populations.

Wang and Banzhaf (2018) reviewed the evolution of GI definitions, mapped GI approaches, and performed a functional analysis using the principles of GI. They state that GI balances the conflicts between man-made infrastructure and natural ecosystems and that this requires multi-scalar and multifunctional approaches. However, they found that some studies use GI without any distinguishing description, considering it as synonymous with green areas or urban vegetation (Wang & Banzhaf, 2018).

GI provides a platform for natural processes that function as an engine and generate multiple ecosystem services for residents. Ecosystem services are the benefits that people obtain freely from well-functioning ecosystems. They include four type of services: supporting, provisioning, regulating, and cultural services. These services are provided by the platform that GI generates. The connection between GI and ecosystem services is made in several studies (e.g. Cameron et al. 2012; Loram et al. 2007a; Tzoulas et al. 2007).

Although the general approach to GI in planning practices includes both private and public green areas within the concept of GI, there is also some discrepancy regarding the role of private gardens. Some definitions directly mention private gardens (AILA, 2012) while others refer to them indirectly (*Green Infrastructure Guidance*, 2009; Sandström, 2002) or leave their inclusion open to interpretation (Benedict & McMahon, 2006). Notwithstanding ambiguities in the definition, Payne and Barker (2016) found that only 53% of homebuilders in the UK considered their gardens to be a part of GI.

In addition to GI, the concept of nature-based solutions (NBSs) has emerged to address environmental, community, and economic challenges by imitating natural processes. Eggermont and colleagues (2015) state that NBSs concentrate more on the complexity and dynamics of socioecological systems than on technological strategies. They found that NBS frames put either the economy and social assets or biodiversity and local communities at the heart of NBSs that provide ecosystem services. By definition, these framings link the biophysical environment to ecosystem services in the same manner as GI, and there does not seem to be a clear or solid difference between GI and NBSs. However, NBSs stress the role of stakeholders and the dynamic nature of solutions that leave room for self-reorganisation and associated resistance and resilience capacities (Germastani & Benson, 2013). Within this theoretical positioning, NBSs may be considered more as a solution to specific challenges experienced by society and GI more as a biophysical and spatial platform.

The previous concepts are based on the connection between the biophysical environment and sociocultural and economic issues, although they vary and are still developing. The biophysical environment may also be comprehended as a set of separate but interconnected ecological components that evolve relatively slowly. This backbone of the urban environment forms a base for all the biophysical components behind, or under, the urban form and layout. These biophysical components were first presented for land-use planning by Ian McHarg (McHarg, 1969) as an ecological method (Carlsson, 2017). The ecological method involves the collection of cross-disciplinary data, which are subsequently interpreted and evaluated to identify suitable locations for different land uses in an ecological context. The novelty of this method relates to abiotic and biotic factors within the physical environment. Although McHarg did not use the concept of GI, the preliminary potential of GI in any land-use category rests on the layers found in McHarg's ecological method (Figure 6).

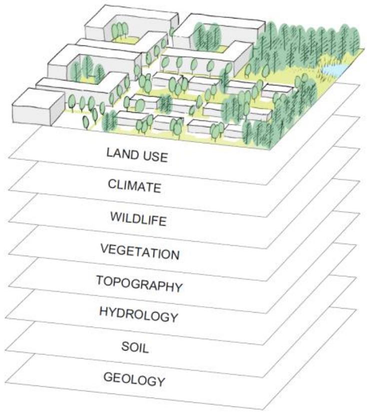

Figure 6. Ian McHarg's approach to landscapes focused on analysing the layers that form the landscape structure. In the urban context, all these layers, which include both abiotic and biotic factors, form the geophysical environment. This approach links hydrological regimes to different habitats for use in planning. (Figure, O.Tahvonen)

2.1.2 System thinking

All the concepts presented in the previous section have been developed through system thinking, which is aligned with the approach to the city as a complex and dynamic system. Thus, urbanisation, as a megatrend, requires new ways of thinking about cities and their wicked problems. Cities are, and will always be, ever-changing systems of which urban green is one of the functioning parts and is integrated with other urban structures, functions, and processes. In an urban context, system thinking is a concept that includes all urban subsystems as structures, all functions, and all processes in one complex, dynamic system. According to system theory, the division of the whole into parts and their separate analyses cannot provide a full understanding or explanation of the functioning of the whole system. It is important to concentrate on interactions and dependencies between different elements or subsystems rather than analyse their individual properties (Bertalanffy, 1968). Figure 7 depicts how different networks or subsystems operate in a complex system.

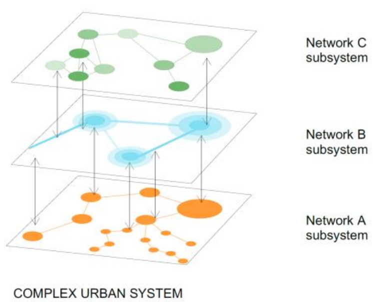

Figure 7. Systems include several layers of networks, and the main interest in system thinking is the connections and feedback within the system. In an urban context, this approach locates GI with a more complex framework, which is undergoing continuous change. (Figure, O.Tahvonen)

System theory states that systems operate through cyclic processes rather than linear models. Therefore, the evolution of the system might involve iterative loops, self-regulating processes, and deep interactions between the elements that form the system. This also applies to the design and planning of locally adapted sustainable solutions.

Two concepts related to urban green support system thinking (Figure 8). First, ecosystem services are the benefits that people gain from a well-functioning ecosystem, where functioning refers to factors such as carbon, water, and nutrient cycles. This functioning takes place in a biophysical entity that is both man-made and developed by natural processes. Therefore, any modification to or action of construction in a biophysical entity affects the processes of its ecosystems. This approach tightly links GI and ecosystem services together as a system.

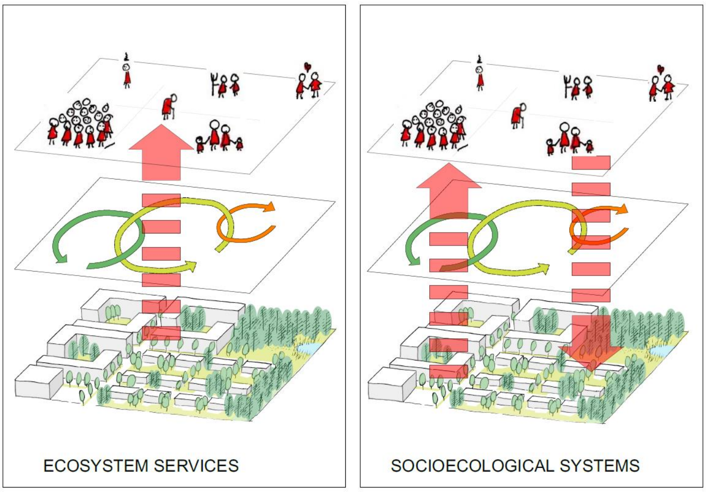

Figure 8. System thinking integrates a human or a resident layer more securely within the concept of urban green. Ecosystem services are defined as the benefits that residents gain from ecosystem. Socioecological systems emphasise the feedback loop of residents that may provide ecological improvements. A more general approach to system thinking stresses a holistic understanding that includes multiple regimes and ongoing changes that may be evaluated by the concept of resilience. (Figure, O.Tahvonen)

Second, the constant interaction and change in the human and biophysical environment might be considered under the concept of a socioecological system (SES). Redman and colleagues (2004, 163) defined an SES as a “coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner; a system that is defined at several spatial, temporal, and organizational scales, which may be hierarchically linked; a set of critical resources (natural, socio-economic, and cultural) whose flow and use is regulated by a combination of ecological and social systems; and a perpetually dynamic, complex system with continuous adaptation.”

In this context, residents’ activities are perceived as one type of functioning, along with the ecological functioning of the biophysical platform. However, this interaction is not perceived as uniquely destructive but as a framework for exploring new opportunities. Residents’ activities can produce novel ecosystems in residential areas, which implies that an ecosystem is permanently altered by interactions with sociocultural systems (Ellis, 2015). This kind of nature is one component of GI. It functions as an ecological network but is defined by its dynamic nature and anthropocentric premises. These processes may also be divided into biophysical and social processes (Demuzere et al., 2014).

2.1.3 Scales

System thinking involves the idea of several mutual subsystems functioning at the same time on several spatial and temporal scales. Although systems function on multiple interconnected scales, system thinking focuses on the entity and its holistic functioning rather than on individual elements or networks of single elements. The multi-scalar approach has strong roots in ecology, but in other fields, it can be comprehended in many different ways. Scaling may define the modular replication of a certain element or structure, which in the case of stormwater management, for instance, can consist of a network of replicated standard construction elements. Scaling may also refer to resizing when the physical size is simply zoomed either in or out. This approach may cause malfunctioning in stormwater management if the expanded structure does not fit the resized physical environment. Scaling also refers to spatial and temporal dimensions, and these seem to represent the most common use of scaling for understanding ecological patterns and processes (Schneider, 1994). In the case of GI, Abunnasr (2012) uses the terms horizontal and vertical scales, where vertical especially refers to scales from the site to the region level, and horizontal to the transect from urban to rural systems. However, the concept of horizontal

and vertical scales is used in multiple ways. i.e. Leese and Meisch (2015) identified horizontal scales and cross sectoral and vertical among different levels of administrative authorities.

Within this conceptual framing of the urban green, this dissertation uses the concept of GI to refer to a holistic, scalable, connective, and multifunctional system of green spaces (Table 2). This biophysical environment includes a set of GI elements and areas with multiple typologies at different scales. This entity may be considered a spatial network. The framing clearly separates the concept of ecosystem services from GI, although some studies and the definitions they offer seem to merge these two. The separation of these concepts is supported by Ely and Pitman (Ely & Pitman, 2014) who classify GI studies into three main approaches: (1) GI as a platform for ecosystem services, (2) GI as connective linkages, analogous to conventional engineered networks, and (3) GI as a tool for specialised green engineering, concentrating on measures such as green roofs, living walls, and bioretention as a ways to purify surface runoff.

Table 2. The key concepts and their description defined by the author.

Key concepts	Description
Green infrastructure	This includes all the urban green that provides a multifunctional platform for ecological cyclic processes. GI includes both private and public components of the urban green. It corresponds to the concept of actual green structures but concentrates more on connectivity and spatial multifunctionality. Definitions vary according to the scale at which planning is implemented (Allen, 2012)
Ecosystem services	These refer to the set of benefits people gain from well-functioning ecosystems, which are based on ecological cyclic processes. They constitue a human-centric approach that may assign monetary value to the functioning of ecosystems but not to the actual biophysical environment. In an urban context, ecosystem services are gained from ecological networks and man-made structures.
Socioecological system	An SES stresses the feedback loop in ecosystem services, where human activities have an impact on an ecosystem's functioning. It is a coherent system that takes place at several scales, combining social and ecological systems and continuously adapting to the changes in the environment. In LDH, SES is an ongoing process between GI and ecosystem functioning influenced by residents.
Scalability	Scaling refers to connections between different scales and, in this dissertation, ranges from the detail level to plots, blocks, and neighbourhoods. It is notable that the spatial scales in ecology do not directly correspond to the scales in planning and design. Scalability means the capacity of planning and design processes to realise multiple scales and recognise the possibilities of garden-scale choices to improve upper-scale factors.

2.2 Scalable green infrastructure

Although GI is a multidimensional concept, several general **principles** apply to it. The main principles are generally common to several studies and projects. Mell (2010) lists the principles of GI as a) connectivity, b) access, c) multifunctionality, and d) strategic planning but notes that these principles are weighted differently in different areas. In a later study, Wang and Banzhaf (2018) list six principles to describe the main characterisation of GI: a) sustainability, b) multifunctionality, c) connectivity, d) biodiversity as the target, e) urban focus, and f) collaboration. Hansen and Pauleit (2014) summarise planning principles as a) integration, b) multifunctionality, c) connectivity, d) a multi-scale approach, and e) a multi-object approach. Regardless of how these GI principles are formulated, they convey an idea of GI as including the overall urban green and being resilient. Of these principles, multifunctionality, connectivity, and scalability are within the scope of this dissertation to form a background for scalable GI in LDH.

Other more detailed studies have been conducted, especially on the topic of **multifunctionality** (Hansen & Pauleit, 2014; Mell, 2010). Multifunctionality initally refers to the generation of multiple functions simultaneously in the same spatial area. However, Hansen and others (2019) point out that the principle of multifunctionality may also be comprehended as the functioning of ecosystem services. In the context of GI, multifunctionality means a broad understanding of functions.

Multifunctionality connects the approaches of GI and sustainability. The idea of sustainability rests on the simultaneous occurrence of the three pillars of sustainability, and, similarly, GI's multifunctionality rests on three main components (i.e. ecological, economic, and sociocultural functions), relating the whole concept to sustainable development and its triple bottom line (Hansen et al., 2019; Mell, 2008). Based on this approach, GI is considered a biophysical platform that provides sites for natural processes, which then provide ecosystem services for people. Optimisation of this functioning in urban areas requires a multifunctional use of space, especially in dense cities. Therefore, GI's strength lies in multifunctionality (Brandt & Vejre, 2004; European Commission, 2012b). In general, multifunctionality is a more tangible concept than sustainability, although both have the goal of creating more resilient cities (Wang & Banzhaf, 2018).

Herzog's (2016) list of GI's functions links it to Ian McHarg's ecological method, presented on page 16-17, which refers to layers of landscape structures. Herzog's list includes functions related to geology, hydrology, biotic elements, and social elements (Herzog, 2016), whereas McHarg's method includes geology, physiography, and hydrology, as well as soil characteristics, climate, vegetation, wildlife, and sociocultural phenomena (Carlsson, 2017). When considering GI's multifunctionality with regard to the pillars of sustainability, social functions come to the forefront in the urban context: multifunctionality includes the urban realm with human-orientated needs, uses, and values and their effect on all land-use categories in cities. The effect may be unfavourable for nature, but it may also support ecological functions.

Green infrastructure's principle of **connectivity** refers to structural and functional characteristics. Structural connectivity refers to the network of elements and areas forming the biophysical platform of GI, whereas functional connectivity relates to the services and benefits the biophysical background provides as acosystem services. In addition to spatial connectivity, connectivity can also refer to connectivity between social and ecologal functions. In practice, connectivity is the property of landscapes that illustrates and builds on the interactions related to a landscape's structure and function (Ahern, 2007), such as water flow and the nutrient cycle. However, Kambites and Owen (2006) use connectivity to refer to the connections between different human users, to administrative connectivity, or to connections between different parts of the organisational structures of local authorities.

Green infrastructure research has also focused on its individual features or **elements**. These concrete elements are mapped and evaluated in different ways and at several scales. On the regional scale, GI elements may include nature reserves, forests, river corridors, and working farms. Zooming into the city scale, the elements are mapped as urban forest patches, parks, the tree canopy, and connective corridors in the form of parkways and boulevards. However, some studies also demonstrate the drawbacks of concentrating on features that are not on the same level, or even comparable, such as green roofs and urban forests. If a set of individual and concrete elements are simply mapped, their connectivity and functioning as part of a system may be ignored. Moreover, GI studies that ignore site-scale solutions and concentrate solely on large-scale connections, fail to recognise the potential of bottom-up phenomena and the power of small choices on the plot scale.

Scalability, or scaling of GI, is the key principle that combines the principles of connectivity and multifunctionality. An adequate understanding of single GI elements requires a scalable approach, which can visualise the total network that these elements form. Scaling can be operationalised in several ways. Some studies and projects use both a multi-scale and single-scale approaches to address several issues (Allen, 2012; Demuzere et al., 2014; Golden & Hoghooghi, 2017; Livesley, McPherson, & Calfapietra, 2016; Shuster & Rhea, 2013). The idea of scalable GI rests on a two-way approach. The overall green system and its strategic planning of that system reflect and guide detailed solutions on smaller scales. Conversely, the most detailed solutions for stormwater management or green roofs influence upper-scale connectivity and multifunctionality. The diversity of scales is addressed in various articles on large national ecological networks (Weber & Allen, 2010), local stormwater management (Ahern, 2007), green roofs and facades (Harper, Limmer, Showalter, & Burken, 2015), and neighbourhoods (Peng & Jim, 2013; Williams, Lundholm, & Scott Macivor, 2014).

According to Cook (2012), single-scale analyses of residential landscapes have been conducted from both a social perspective (Askew & McGuirk, 2004) and an ecological perspective (Sperling & Lortie, 2010). Research has also been conducted on the household scale (Larson, Casagrande, Harlan, & Yabiku, 2009; Smith, Thompson, Hodgson, Warren, & Gaston, 2006) and on broader scales in the study of land-cover patterns (Grove et al., 2006). Multi-scalar studies have sought to identfy an appropriate set of scales in the context of GI. Allen (2012) used the site scale to focus on low-impact development, urban forestry, and stormwater management. On the regional scale, he concentrated on green space provisioning for water management, greenways for recreation, and, on the 'landscape' scale, he focused on network design for species habitats, wildlife corridors, and compatible working landscapes. It is notable that Allen uses the term 'landscape' scale to refer to supraregional scale that does not fully correspond to the concept of landscape in landscape architecture. Livesley and colleagues (Livesley et al., 2016) used the scales of a tree, a street, and a city for their GI study, while Davies and colleagues (2006) suggest using the scales of individual elements as a basis for GI in parcels, linked elements as networks, and GI as an overall infrastructure.

The challenge of working with scales lies in the fact that the stakeholders, tools, objectives, and type of analysis required are scale-specific. Scale also relates to the levels of risks and benefits that planning may produce. Steinitz (2008) states that, on a large scale, when dealing with strategies, risks and benefits are high, while on a small scale, risks are low. On a large scale, decisions are made by experts and politicians, but on a small scale, everyone makes decisions. In the context of stormwater management, this may also apply to the biophysical layout of centralised and desentralised solutions and their role in the overall system.

Philips (2016) recommends identifying and focusing on the most important or interesting levels and then working either top-down or bottom-up from there. He claims that scaling is easy as long as the processes and functional relationships remain unchanged. However, typically, they do not. Scaling ought to involve a multi-scalar working method in planning and design practices rather than working separately on different scales. This working method is difficult to present, although educators in planning consider it to be the common working method.

A block-scale layout in LDH areas frames the plot-scale arrangement of buildings and main vegetation patches. This generated landscape pattern defines the potential for ecological functioning in these areas (Forman, 1995a).

2.2.1 The core system of green infrastructure: soil, water, and vegetation

Having studied different GI scales, Allen (2012) claims that the widest scale focuses on landscape ecology and the biological principles of conservation. The intermediate scale builds on connections between the water supply, quality management, and recreational corridors. Furthermore, he stresses that the site scale's main focus is on the use of SUDSs to build water systems and, in urban forestry and habitats, to expand vegetation networks. When considering water and vegetation within a coherent system, the set of SUDSs needs to be studied more carefully.

The central tenet of GI is the use of plants and the processes essential to plant growth (Fletcher et al., 2015). However, interpretations in various professions may concentrate solely on stormwater management with the goal of imitating processes in the natural water cycle (Fletcher et al., 2015; Wright, 2011). These processes do not necessarily include vegetation. Stormwater infiltration through a sand filter provides an efficient, clean method of stormwater management in which vegetation does not play an active role. Pitman and colleagues (2015) combine these two factors and claim that **water and vegetation** are the most fundamental elements of GI.

Zooming in to this fundamental integration of water and vegetation reveals a finely balanced system that incorporates the water cycle, plant growth, and the soil that connects water and vegetation (Figure 9). In this system, soil is the interface between vegetation and water that enables water to filtrate, be retained, infiltrate, and rise due to capillary action. In turn, vegetation absorbs the available water for its growth and releases water into the atmosphere. The decomposition of dead leaves and biomass forms organic matter (OM), which contains nutrients needed for growth and improves soil's water retention capacity, which, in turn, supports the availability of water for vegetation between rain events. Organic matter supports the living conditions of microorganisms and, hence, improves biodiversity in soil. The development of root systems also supports water infiltration.

The flows of water and nutrients are determined by the characteristics of the existing soil in natural environments and in growth media in landscaped areas. Soil is one of the key components used to define growing conditions in natural environments and in built-up areas. Even developed sites with sand-bed-based paving provide soil conditions that define the balance between water retention and infiltration capacity. Such soil conditions can lead to plant growth in the joints and cracks (Forman, 2014) and these tiny areas are also a component of GI.

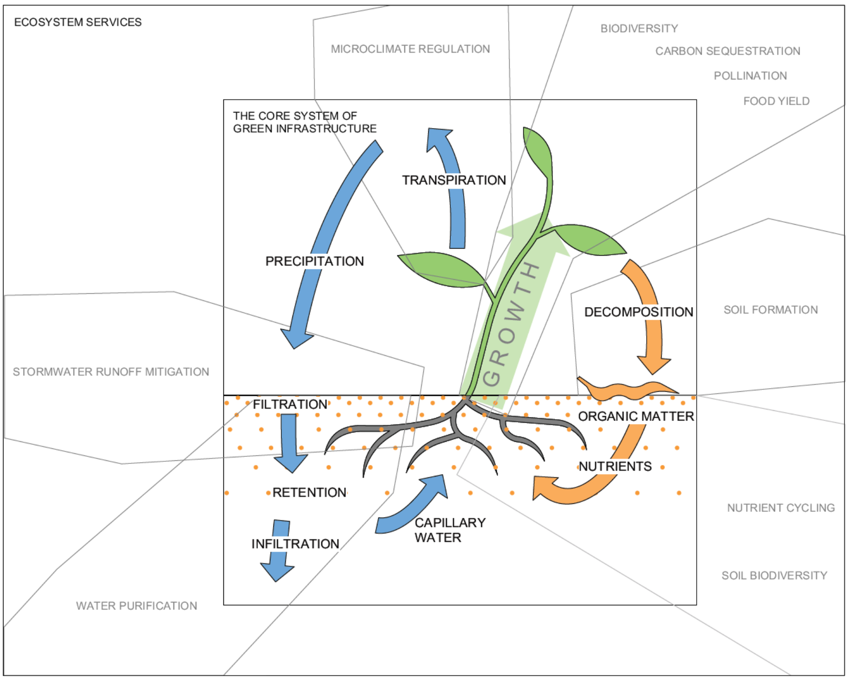

Figure 9. The core system of GI combines water and carbon cycles through soil. These fundamental elements of GI provide ecosystem services when the system functions properly. (Figure, O.Tahvonen)

Green infrastructure's core system of interconnected water, vegetation, and soil qualities, and flows are crucial for the functioning of GI at all scales. Based on general system theory, the main focus is on the whole rather than separating the factors and analysing them as separate elements (Bertalanffy, 1968; Xu, 2015). **Systems** exist on a wide range of scales, from subatomic to universal (Everard, 2013), and multi-scalar thinking involves dynamic linkages between different scales (Chen, 2015). The relationships between ecological processes are often non-linear (Conroy, Allen, Peterson, Pritchard, & Moore, 2003), which makes it impossible to use direct multiplication or divisioning when zooming in or out. The value of an urban forest does not rest on a set of single street trees, even if the number of trees is equal. Different processes and qualities on different scales make the role of scalable GI reasonably dynamic. Therefore, scalable urban GI may be perceived as a system especially influenced by humans and, therefore, a result of the interaction between societal and natural processes (Opdam, 2018). Allen (2012) considers GI within the frame of SES where 'everyone can play a part in maintaining, enhancing, and restoring GI' (p. 23).

The main factor preventing the functioning of the core system of GI, the system of water, soil, and vegetation, is soil sealing in urban environments. **Sealed surfaces** block soil from receiving resources from sunlight and water and collects and convey rainwater to sites that are further away and out of reach. Furthermore, soil sealing and the construction layers below asphalt, paving, and decks all limit the available soil volume for GI's core system.

However, the idea of GI's core system is transferable to limited conditions, such as green roofs or facades, deck gardens, or even planters, where the soil volume plays an important role in water-retention between rain events. In these cases, if the soil volume is too low or poorly defined, plant growth requires external resources in the form of irrigation or fertiliser. The main focus with regard to fostering the ground-based functions of GI lies in controlling the proportion of sealed surfaces. Non-sealed surfaces allow GI's core system to function freely in an open soil system.

Soil sealing primarily concerns paved and built areas, which are identified as the ecological matrix in an urban context. Urbanisation and the rapid growth of **sealed surfaces** are the greatest threat to urban streams (Stone, 2004). Imperviousness refers to all surfaces through which water cannot infiltrate, such as asphalt and paving, as well as roofs. It affects the hydrology, habitat structure, water quality, and biodiversity of the aquatic ecosystem receiving the runoff. Arnold and Gibbons (1996) and Schuler (1994) have stressed the importance of impervious coverage for receiving waters, which should maintain the capacity to handle changes in the quantity and quality of runoff generated from impervious areas and the ability to recover from changing loads. It seems clear that imperviousness as low as 10% in a watershed causes the degradation of water courses (Schueler, 1994; Schueler, Fraley-McNeal, & Cappiella, 2009). The outcome of soil sealing is a disturbance in the natural water cycle, at loss of ground-connected vegetation surfaces, and increased surface temperatures (European Commission, 2012a). Brauste (2011) claims that urban soil sealing is the key indicator of urban ecological functionality. This shows that a system comprised of water, vegetation, and soil exists when the soil is not sealed. Furthermore, Artmann (2014) argues that it is necessary to control urban soil sealing in order to control surface runoff and prevent high expenses and the loss of agricultural land and urban green.

A common, widely-accepted planning tool used to support and enable ecological qualities in any land-use category is the limitation of impervious coverage.

Urbanisation generates soil sealing, and the European Union's in-depth report on soil sealing (2012a) lists urban sprawl, car-dependent lifestyles, and paved gardens as examples of the main drivers. Some cities use impervious coverage and its extent in percentages (i.e. the total impervious area [TIA]) as an indicator in land-use planning to predict the ecological impact of planned construction and to estimate of pollutant loads from different land-use categories(Kuusisto-Hjort & Hjort, 2013).

The concept of an effective impervious area (EIA) can be applied to describe the functioning of impervious areas in more detail. An EIA includes only the impervious areas that are hydrologically connected to a storm sewer system. The concept was developed to address the need for accurate calculations and GIS-based studies (Roy & Shuster, 2009). An EIA or, rather, its opposite metric, also provides insights relevant for GI. As EIA describes the area that is hydrologically connected to the centralised drainage system, it can also be used to identify all the other areas that are not. Identifying the proportion of impervious coverage that is not connected to a stormwater sewage system is useful for site-specific stormwater management. Impervious coverage, when it is not connected to the sewage system, provides a resource for site-specific use.

However, the management of urban soil sealing is difficult. Artmann (2016) identifies the factors that contribute to this difficulty, noting that spatial heterogeneity is very high in urban areas, and that soil sealing is embedded in conventional SESs. She claims that the key issue is the management of SESs to protect GI as the spatial complexity of urban areas has ecological effects, such as microclimatic, biodiversity, and runoff changes, and also influences human interactions between individuals, governmental regulations, firms, and households. This implies the need to develop new urban planning tools to manage and work with SES and to controll impervious coverage.

These approaches to soil sealing and impervious coverage highlight the importance of scale. Soil sealing provides tools for the watershed scale and the site scale. Indeed, in GI planning, scaling and multi-scalar functionality are mentioned as two of its characteristic qualities. More generally, scale is also mentioned as the key issue in sustainable planning to examine the connections and interdependencies of sites and ecosystems (Leitao & Ahern, 2002). Demuzere (2014) identifies the typical pitfalls of scale-orientated water management, where the site scale may fail to address connections between sites, or network-scale planning may ignore the degradation of the whole system. However, improved water quality and at reduced probability of flooding, peak flows, and drought are relevant on all scales.

2.2.2 Green infrastructure as an ecological network

Green infrastructure is perceived as an ecological network with connective corridors and habitat provisioning. This network provides habitats for endangered species and links patches to create corridors (Allen, 2012). In this approach the main principle of GI is, therefore, connectivity.

Forman and Godron (1986) defined the basic elements of urban ecology as patches, corridors, and a matrix. Using this widely used **model of patch, matrix and corridor (PMC)**, ecological planning has focused on conservation areas or other ecologically valuable areas, such as patches. To meet planning needs, the minimum size of patches and the space for linking them through ecological corridors must be defined. In an urban context, this ecological network also refers to a network of recreational areas for residents and an environment in which fauna can live and navigate. However, this approach may understate the ecological value of the third factor, the matrix, which covers all areas outside the corridors and patches. The matrix is the dominant land-cover type, and Forman (1995) notes that it covers at least 50% of the total area.

In an urban context, the areas of the matrix are typically man-made antropocenes, which correspond mainly to buildings and the transport network, and whose ecological value is not always admitted. Francis and Chadwick (2013) claim that the PMC model considers the **matrix** background land use even if it is the most abundant form. Furthermore, Werner (2011) recognises two aspects of the urban matrix that are underestimated: the habitat it provides for flora and fauna and the permeability it provides for flora and fauna to move through the area. The unclear ecological role of the matrix arises when habitats are described in terms of fragmentation, for example, shrinkage, attrition, and increased isolation, as these words imply an isolated matrix rather than a habitat (Leitao & Ahern, 2002). However, Ignatieva and colleagues (2011) note that urban ecological networks are defined differently in ecology, urban planning, and landscape ecology and that, therefore, the ecology of the urban matrix has recently garnered interest in several related disciplines.

On broader scales, the characteristics of an area identified as a matrix depend on the current land-use qualities. Different land uses frame surface coverage patterns and, thus, the vegetation coverage and degree of soil sealing. These two **indicators**, vegetation coverage and soil sealing, generally describe an area's ecological functioning. Werner (2011) argues that the amount of urban vegetation can be used as an indicator when evaluating the ecological characteristics of an urban matrix. Biodiversity is also a relatively well-studied factor of ecology in an urban matrix. Semi-natural areas, such as wetlands and abandoned industrial areas, may foster richer biodiversity than some green areas (Lyytimäki, Petersen, Normander, & Bezák, 2008).

Urban ecology is beginning to recognise the complex structure and functioning of an urban ecosystem and the role of a matrix in planning practices, management tools, and the identification of ecological functions. Urban planning with mono-functional land-uses needs to serve the space required for the main function of a given land-use category; however, it also defines the potential of GI as a secondary function and a cross-cutting theme. Furthermore, the entire urban area consists of a series of biotopes of different types and these areas are important for the urban matrix, even if they are unworthy of protection or if they are put to extreme use (Starfinger & Sukopp, 1994).

An urban matrix is a man-made, constantly changing built-up environment that has a significant effect on the people who work and live within it (Miller &

Hobbs, 2002). These areas form an entity that could not be restored to its natural condition even if human activities and structures were removed. Marris (2011) claims that cities simply no longer have the option of disregarding these areas due to urbanisation, population growth, and the evident lack of 'original' or 'natural' habitats.

However, the traditions and presentation techniques in urban planning do not fully support the represention of multifunctionality or the changes taking place in planned areas. Planning, as a process, aims to be completed at once, and as a tool, it is not meant to be reconsidered very often. Spatial plans in Finland are typically documents that are valid for 10–25 years. Multifunctionality and change pose challenges for planning processes and representation techniques, but they are necessary factors to consider with regard to the management and sustainability of an expanding urban structure.

The nature of GI means that it provides significant possibilities for ecological urban planning. Patches and corridors may be supported by areas of the matrix that possess certain qualities. This ecological land-use complementation was first presented by Colding (2007), who stresses the usefulness of the concept to support ecological resilience when building new developments. This approach is based on the ecological qualities in all land-use classes. Hence, it guides planners to consider tools and guidelines based on ecological functioning, even if urban green is not the land-use category's current, primary function. This integrates residents' actions into areas of the matrix to improve the areas' ecological functioning and, therefore, challenges conventional planning practices. The most traditional determinants, such as the use of an area, its location, or allowed housing density, do not directly control ecological qualities in GI.

2.2.3 Green infrastructure on the site-scale: A water-based reflection

The recent interest in GI from researchers includes conceptual research and practical applications (Mell, 2008). Water plays a major role in site-scale GI in an urban context, where soil sealing generates runoff and climate change adaptation requires new tools for stormwater management. This section presents various stormwater-centric approaches to site-scale GI to demonstrate their relevance for the other components of GI's core system, soil and vegetation. Soil and vegetation are less often regarded as playing the main roles in GI at this scale.

Green infrastructure's site-scale solutions for stormwater management are covered by the concept of sustainable urban drainage systems (SUDSs) or best management practices for water-sensitive cities. These approaches provide an alternative to conventional quantity management in centralised sewers in the form of a wide collection of standardised details. In general, these practices sustain the existing local hydrology by emulating the natural hydrological cycle and are focused on above-ground solutions (Lähde, Khadka, Tahvonen, & Kokkonen, 2019).

Based on their ability to operate as a substitute for conventional drainage, the role of vegetation or moisture provisioning for habitats was not initially considered a key issue for SUDSs. However, SUDSs are often mentioned as site-scale

GI solutions since the number of SUDSs is high, and there are a wide variety of related practices that provide local management with tools for sustainable stormwater management. To gain a general understanding of the uses and mechanisms of SUDSs, there are several possible ways to categorise them. First, SUDS can be classified according to the process of the water cycle they are emulating (Figure 10). Charlesworth and colleagues (Charlesworth, Warwick, & Lashford, 2016) use the main themes of source control, infiltration, retention/storage, conveyance, and quality improvement. These basic processes may take place either above ground or under the surface, or they may follow more technical or NBSs. The common denominator in these themes is hydraulic processes. This approach may integrate vegetation and soil in some SUDS, but the systemic nature of GI's core system occurs mainly in bioretention, which refers to the infiltration, storage, evaporation and filtration of stormwater in a shallow depression that is vegetation covered and has modified soil layers.

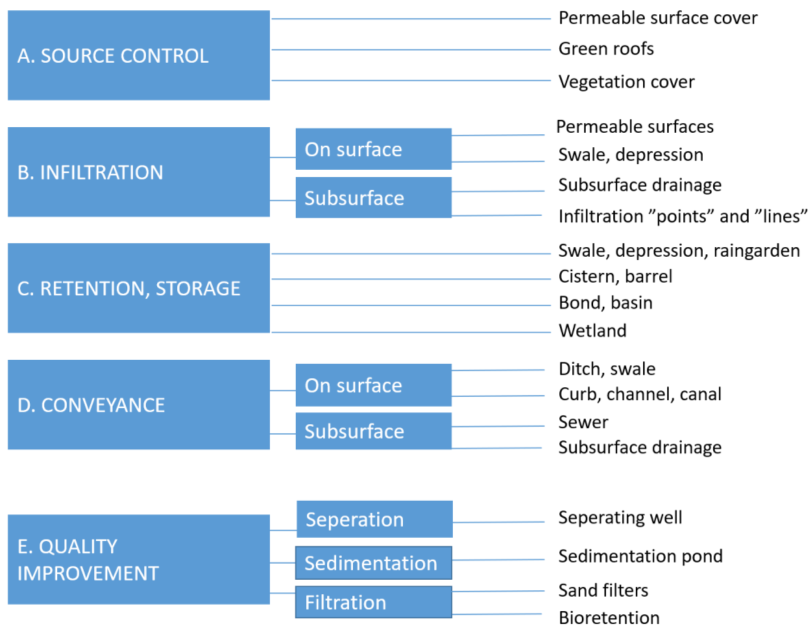

Figure 10. SUDS classified according to the main processes of the general water cycle and the individual processes they emulate. (Figure, O.Tahvonen)

The second way to categorise SUDSs is according to their location in the drainage area or, more generally, the watershed (Figure 11). Typically the upper and lower parts of a watershed present different challanges. The upper parts only handle the precipitation they receive, whereas the lower parts also need to handle the surface runoff received from the upper parts. Therefore, different methods are suitable in different locations of a drainage area or subwatershed. The choice and use of different SUDS should be based on their location within the drainage area or subwatershed alongside its planned main function (Figure 11). However, plot-scale stormwater management in an urban context is restricted to drainage at the origin or upper parts of the watershed as local regulations in

Finland prohibit allowing surface water to run across boundary lines to neighbours. In practice, this means that plot-scale designs must concentrate on source control, infiltration, retention, and storage rather than conveyance to other locations. In general, the set of management practices are combined somewhat differently when designing decentralised rather than centralised solutions. Furthermore, decentralised practices are located primarily on private land, such as plots and their gardens, whereas centralised stormwater management is more commonly located on public land in open spaces and streets.

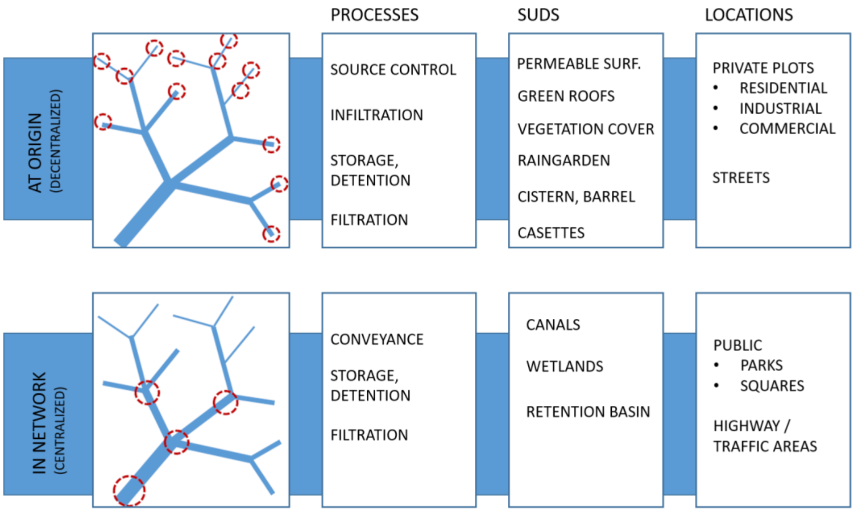

Figure 11. Different SUDSs fit different locations in a drainage network due to their different capacities to prevent runoff and manage runoff already generated. (Figure, O.Tahvonen)

The third way to categorise SUDSs entails zooming out from a single SUDS. There seem to be two main approaches to wider entities. The first concentrates on combinations of single SUDSs as treatment trains, and the other is based on areal surface materials and the volume and water-holding capacity of their construction layers (Figure 12). The latter approach is used as a green factor that aims to ensure there is a sufficient proportion of vegetation-covered surfaces in the building permit process (Skärbäck, 2007). The concept of green factor (GF) not only applies stormwater management, although there are criteria for SUDSs (Kazmierczak & Carter, 2010). However, GF includes the idea of valuing planted areas, and more points can be gained if more deep-growth media layers are used (Calvet-Mir, March, Nordh, Pourias, & Cakovska, 2016). This is connected to soil volume and, hence, an area's capacity to hold storm-water. However, a combination of single SUDSs is presented as a network of SUDSs, which is called stormwater a treatment train. The whole treatment train defines the site-specific functionality. Therefore, an individual SUDS does not exclusively determine the optimal functioning of the whole treatment train. This facilitates the integration of stormwater management with other design objectives. Thus, design by treatment trains uses different SUDS mainly for quality and quantity management, but they may, also include the components of soil and vegetation.

The role of soil and vegetation is more significant in the case of surface-area-based scoring, such as Green Area Factor, especially if the scoring guides the design to maximise the vegetation coverage instead of generally identified non-sealed surfaces.

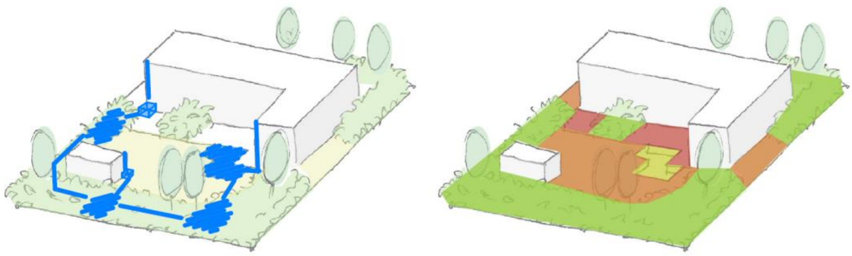

Figure 12. Plot-scale stormwater management approaches: SUDS arranged in band-like treatment trains that consist of several SUDS (left) and GFin the form of surface-area-based scoring factors based on landscaping choices and soil volumes (right). (Figure, O.Tahvonen)

The fourth way to describe SUDSs is based on their capacity for multifunctionality or to provide multiple ecosystem services (Liquete et al., 2015). The British Construction Industry Research and Information Association (CIRIA) defines four objectives for the design of SUDS (Kellagher et al., 2007). The guidelines aim to support design practices that simultaneously provide water quality and quantity management, amenity, and biodiversity (Figure 13). However, site-specific conditions or the objectives of land-use categories may require prioritising one of the objective over the others. This generates the fourth way to categorise SUDSs, based on the practices that prioritise quantity control, quality control, amenity, or biodiversity, although all these objectives are present at some level.

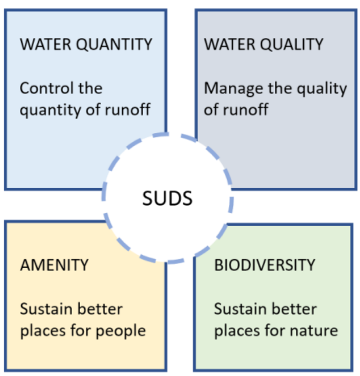

Figure 13. Multifunctional stormwater management includes mutual objectives and functions that are described by the construction industry researchers and the information association CIRIA as quantity and quality control, provision of amenity, and support for urban biodiversity in SUDS. (Figure modified from CIRIA)

In contrast to the initial and strictly hydrological approaches to SUDS, new approaches that aim at enhancing biodiversity and amenity highlight the role of vegetation and soil. Otherwise, SUDSs seem to focus on water management, and the benefits related to soil and vegetation are regarden as secondary. This is aligned with the definitions and principles of GI at broader scales which demand more integrative and multifunctional approaches at site-scale and in stormwater management since water is at the core of the GI system.

2.2.4 The core system of green infrastructure from a bioretention perspective

Biofiltrative SUDSs perform several processes involved in the natural water cycle such as filtration, infiltration, storage, and evapotranspiration. However, they also offer an ideal vehicle for a more systematic study of the interactions between the key components of the core system of GI (water, soil, and vegetation). These processes take place in soil and through vegetation and are presented in stormwater management guidelines as rain gardens, street planters, pocket wetlands, and buffer/filter strips (Ellis, 2013). In these SUDSs, vegetation involves increasing evaporation as evapotranspiration produces a visible urban design element and has the potential to support urban biodiversity. The roots of plants also support water infiltration through the formation of root systems or prolong water flow rates in structures that collect water. These functions concern all vegetation-covered infiltration structures as they either follow or adopt the general idea of bioretention.

As a concept, bioretention describes a vegetation-covered stormwater management structure that stores, purifies, infiltrates, and evaporates water, as well as increasing water delay and producing vegetation consisting of multiple plant species. This combines a ground filtration structure with vegetation growth in a depression under which mass transfers or soil amendments have been carried out in the layered soil structure. Thus the basic idea of bioretention is considerably broad and can be applied to several management structures in which vegetation plays a key role in stormwater management. The functioning of bioretention lies in the interrelations between soil, water, and vegetation (Figure 14). These elements must be perceived not only as integrative but also equal and highly interdependent. Detailed design, therefore, balances separate qualities to form a functioning system.

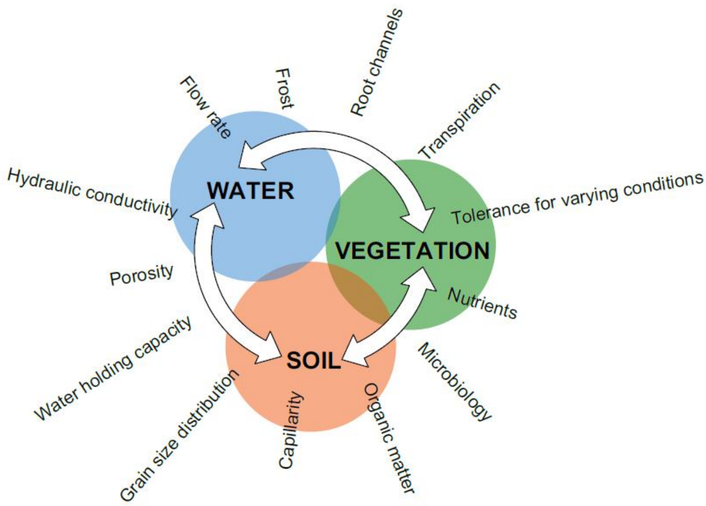

Figure 14. Vegetation-integrated stormwater management encompasses the idea of interdependent elements of water, vegetation, and soil. The system incorporating these factors occurs, for instance, in bioretention-based SUDSs. (Figure, O.Tahvonen)

There are several guidelines and schematic description of a bioretention structure. From top to bottom, the soil layers of the structure include the growth media, a filtration layer, and a drainage layer (Figure 15). In this structure, the most fine-grained soil types are located closest to the surface, and grain sizes increase as the layers get deeper. Therefore, the structure drains via the force of gravity. Various transition layers are used to ensure that the fine aggregate is not carried with the water to the lower, rougher layers.

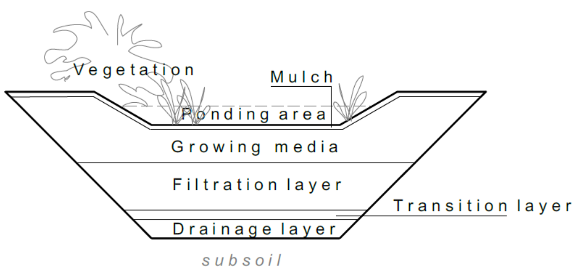

Figure 15. Construction layers and general components of bioretention. (Paper 4, Fig.1)

2.3 Low-density housing and private gardens

The location, extend and density of LDH are defined in a hierarchical and three stage planning system in Finland. First, regional plans guide landuse at a regional scale, but do not specifically differentiate between different housing densities. Second, master plans continue to more specific definitions of the locations of different urban functions, including the extent of LHD, within the municipality. Third, local detailed plan locates different construction sites to local conditions and defines exactly what is allowed to be built. This land-use planning system is framed by nationwide land use goals and participatory processes at every stage. (Jalkanen, Kajaste, Kauppinen, Pakkala, & Rosengren, 2017).

In the range of land-use classes, residential areas provide a multifunctional, heterogenic platform for GI. The set of numerous plot owners and garden users continually modify the platform according to their individual needs, values, and aims. From the perspective of GI, residential areas and, specifically, LDH with detached houses, include private gardens, parks, and street vegetation. In this set of GI elements, the private gardens provide the most extensive proportion of LDH's GI.

The extent of LDH and, especially, its garden coverage has been mapped in a few studies, which mainly originate from Western countries. Loram and colleagues (2007) found that gardens in LDH cover 22% of the studied towns and cities in the UK, and Mathieu and colleagues (2007) found the share to be 36% in New Zealand. Overall, garden spaces in LDH were found to account for 35-50% of coverage in these studies.

The extent of private gardens can also be evaluated based on the population living in detached houses, semi-detached houses, and rowhouses. This approach (Table 3) shows the prevalence of house types that have adjacent private gardens in Finland. In the 10 largest Finnish cities and towns, 25–56% of households are in LDH areas if Helsinki, which is a dense capital area, is excluded. In the whole country, the proportion was 39% in 2017 (Statistics Finland).

An obvious reduction in garden areas in Helsinki's metropolitan area has been identified. In the case of Ylästö, the reduction in garden areas was 72–50% between 1998 to 2009 as infill practices targeted garden areas (Ojala, Niemelä, & Yli-Pelkonen, 2017) .

Table 3. The proportion of single-family or row-house dwellers in the 10 largest towns in Finland in 2017. (https://www.stat.fi/tup/alue/kuntienavainluvut.html#?year=2017&active1=286).

City/town (population)	Household dwelling units	% of household dwellings in single-family or rowhouses
Helsinki (643 272)	330 933	13,3
Espoo (279 044)	122 910	40,5
Tampere (231 853)	124 456	24,7
Vantaa (223 027)	104 180	36,3
Oulu (201 810)	97 284	46,8
Turku (189 669)	102 969	25,6
Jyväskylä (140 188)	71 481	38,1
Lahti (119 573)	63 298	32,7
Kuopio (118 209)	60 031	42,8
Pori (84 587)	44 066	55,8

Urbanisation means that planning of contemporary cities must balance urban densification against urban sprawl. The aim of compact cities is to minimise land consumption, generally by promoting the densification of existing urban areas or by planning new compact urban ones. Tools used for this purpose focus on multifunctional land use and more efficient land use in low-density areas. However, this tends to mean a reduction in the amount of urban green spaces, which, in turn, has shown to increase the number of second homes and the amount of travel to distant recreational areas (Arnberger, 2012; Sijtsma, de Vries, van Hinsberg, & Diederiks, 2012; Strandell & Hall, 2015). This stresses the need for the development of urban planning concepts that include private green spaces within the urban green on all scales. Although GI and green structure include private areas in the overall urban green, planning practices do not always acknowledge the potential of private gardens. The proportion of LDH is extensive, but managing private green spaces using municipal strategic plans seems to be difficult. Figure 16 presents the proportion and locations of LDH in Helsinki's metropolitan area.

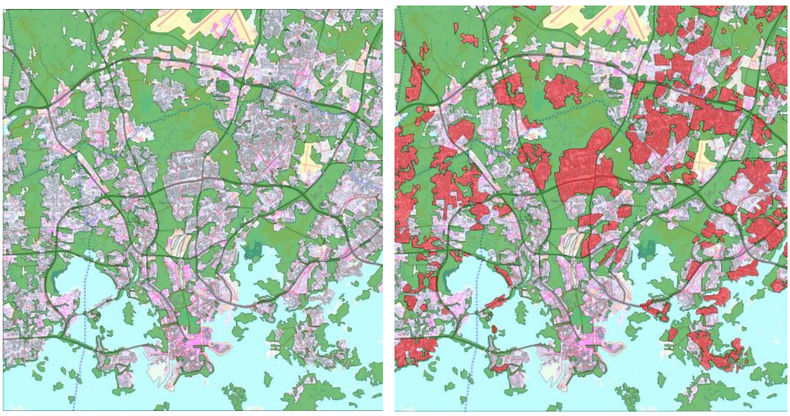

Figure 16. The green area network in the metropolitan area of Helsinki (left) and the extent of low-density residential areas added in red (right). (Information based on open spatial data)

2.3.1 The biophysical platform of LDH

In the Finnish context, municipalities do not consistently collect information about the extent of private gardens or their development (Ojala et al., 2017). This practice arises from the common idea that owners control their own land. Currently, in the age of urban sprawl and densification, this private proportion of land has become one of the main elements in the network of urban areas, and statistics are needed to evaluate the development of this privately owned component of GI.

Private gardens are the main proportion of land that is available for GI in LDH and, thus, for water infiltration and plant growth, which, in turn, relates to the concepts of soil sealing and impervious coverage, as discussed in the previous chapter. Soil sealing is defined in plots, first, by the layout of houses and the main routes for cars and pedestrians, and, second, by the remainder of the plot as a garden space and by the choice of surface materials that provide various levels of permeability. This plot-scale layout defines the plot-scale garden area.

The former is controlled more carefully by regulations and authorities, whereas the latter may be more freely designed by residents and over time.

One of the few studies on Finnish private gardens reveals that garden areas occupy 15% and 27%, respectively, of the total land area of the neighbourhoods of Ylästö and Paloheinä in Helsinki's metropolitan area (Ojala et al., 2017). In these two areas, the average garden area of plots is 552 and 785 m^2, while the garden area of detached houses was found to be, on average, 315 m^2 in some UK cities (Loram, Warren, & Gaston, 2008) and 755 m^2 in a study area in New Zealand (van Heezik, Freeman, Porter, & Dickinson, 2013).

The use and meaning of garden areas depend on their residents, which means that individuals' choices define garden area construction, paving, vegetation, and maintenance, and they, in turn, define a garden's importance for LDH's ecological qualities, its technical performance for improving microclimate and stormwater management, and its social value in terms of social inclusion, self-esteem, and relaxation. The garden's size and, therefore, the plot size, frame the possibilities for these activities. More specifically, the plot's impervious coverage defines the proportion of the garden with the potential for soil-connected vegetation growth. However, this proportion does not equal the garden area because the garden area also fulfils a set of functions that require paved surfaces. Hence, contemporary leisure activities and gardening trends modify plot-scale imperviousness, and vegetation coverage. This type of management defines human well-being, urban ecological functioning, and the continued provision of ecosystem services.

In general, garden resources seem to be well-documented in studies (Owen, 1991; Vickery, 1995), although LDH has only recently been identified as a resource for biodiversity and ecological functioning (Ignatieva et al., 2011; Young, Jarvis, Hooper, & Trueman, 2009). Thus, the value of private gardens and backyards are recognised for their potential to provide ecosystem services, especially habitat provisioning, reduce heat-island formation, and provide public education (Rudd, J, & Schaefer, 2002; Sperling & Lortie, 2010), all of which impacts the entire land-use class of LDH and its qualities for urban planning.

However, individual homeowners effectively form a large group of LDH managers, which adds unique features to land-use planning. Not all gardening practices have a positive effect on LDH's ecological value. One of the most frequently mentioned challenges is the use of alien or invasive plant species that spread and take over the native species, not only in LDH but also in adjoining ecological patches and corridors (Marco et al., 2008). Other disadvantages mentioned are the use of fertilisers that can cause the mobilisation of nutrients, the use of herbicides and pesticides, the use of tap water for irrigation-dependent plants, and the design of large monocultural lawns (Dewaelheyns, 2013; Larson et al., 2012). This set of ecological disservices is also called 'the tyranny of small decisions' (Goddard, Dougill, & Benton, 2010) and is caused by the residents' lack of skill and experience in biodiversity conservation. As Lyytimäki and Sipilä (2009) note, services and disservices are anthropogenic notions that arise from ecosystem functioning, but they are experienced in SESs that integrate individual factors into ecological functions (Tapio & Willamo, 2008).

2.3.2 Private domestic gardens as systems

What if gardens were considered systems instead of biophysical platforms? This section relates plots and their gardens to system thinking in a manner that integrates water, vegetation, and soil systems. System thinking is based on general system theory, which defines a system as a set of interrelated elements that include different connections and feedback loops. This approach was developed to emphasise 'wholeness' instead of mechanical or reductionist ideas (Bertalanffy, 1969). System thinking has proven helpful in combatting a reductionist understanding of the environment (Pullin, Knight, & Watkinson, 2009).

When gardens are considered through the lens of system thinking, it becomes necessary to define them either as closed or open systems. Because private land is based on property rights, it is a result of zoning practices and implies individual plots are generally understood as highly closed systems. This interpretation is supported by local Finnish regulations, which do not allow rainwater to run across borders and forbid plot owners from cutting tree branches growing from neighbouring plots. However, a plot and its garden, considered as soil water movement or corresponding to microbiological connections, is an open system as it includes both input and output flow. Water and vegetation need to be properly considered to enhance their benefits to society. Everest (2013) describes this kind of system as one that has a low-input but multiple-outcomes.

The scalable and multifunctional nature of GI makes it suitable for system thinking. Although this study concentrates on GI, system thinking, at the very least, incorporates human factors. First, the benefits of GI and the processes it encompasses are described as ecosystem services. This concept demonstrates the tight connection between humans and nature; however, the benefits of nature or, in this case, GI, are mainly valued in terms of one-way connections. This one-way process is also visible in the cascade model, which is used to identify a set of ecosystem services (e.g. Hansen & Pauleit, 2014).

The concept of SESs also demonstrates system thinking that emphasises the feedback loop in ecosystem services in the field of GI. Green infrastructure not only provides services for humans, but also means that human-dominated functions define, modify, improve, or weaken the functioning of the natural cycles taking place within GI. This feedback loop may have negative impacts, but recently, it has been studied in terms of improvements and developments in novel ecosystems (Hobbs et al., 2014; Sack, 2013). This feedback loop is an important factor when addressing resilience in LDH.

Calver-Mir and colleagues (2016) introduced a planning-related topic for scalable systems in identifying residents' gardening motivations on the individual, garden community, neighbourhood, city, and regional scale. They claim that, in the context of allotment gardening, motivation related to psychological and physical health relates to the personal scale, but motivations related to learning and education apply to all scales up to the city scale. These motivations may be used to reinforce SESs and develop new connections between society and the environment in residential areas.

Resilience is a phenomenon that is often linked to both system thinking and GI. It refers to the ability of a system to absorb disturbances and still retain its basic functions and structure. Walker and Salt (2006, p. 9-10) claim, 'At the heart of resilience thinking is a very simple notion – things change – and to ignore or resist this change is to increase our vulnerability and forego emerging opportunities. In so doing, we limit our options.' Furthermore, they describe change as sometimes slow and sometimes fast. This supports the view of resilience thinking as a framework for viewing a social-ecological system as one system that incorporates many linked scales in time and space.

Resilience includes the concept of adaptability, which can be transformed to learnability in an organisational or management context. This gives resilience an active role in LDH. Resilience is not something that comes from outside the system but is rather active work, in case of SESs, performed by residents. The ability to adapt to evident and forthcoming changes is, therefore, linked to transformations, such as climate change adaptation, in private gardens.

System thinking includes the idea of multiple scales and a hierarchical order which corresponds to subsystems within systems or a network of different subsystems. In the case of GI in LDH, the core system is seldom defined. It is notable that the identification of a core system is not reductionist thinking but is rather the identification of the element that constitutes the basic layer for system thinking. In the case of GI, it seems obvious that (storm)water, soil, and vegetation are three of the main elements in a garden-scale system, along with the human factor.

A GI system based on these essential elements is contingent on the provision of the maximum amount of pervious surfaces, as GI depends on biological and ecological processes to provide ecosystem services (Abunnasr, 2013). This requires the presence of soil, water, vegetation, and their interconnected flows and feedbacks, which is identified in this dissertation as the core system of GI. This raises the question of the minimum amount of space required for a self-sustaining GI core system. In addition, this core system integrates ongoing ecological processes with residents' purposeful and unintentional gardening activities in the case of LDH. The frame for this system is defined in the processes of urban planning and design.

As ecological conservation is not the main function of LDH, more sensitive and flexible tools are necessary to influence the choices residents make. One possibility is to capitalise on contagious patterns in residential areas, such as the neighbour mimicry effect (Smyslony & Gagnon, 2000; 1998). This effect can be seen when people living on the same street mimic elements and practices observed in their neighbours' plots. These bottom-up practices may be essential when developing a household-scale mechanism of coupled natural and human systems (Nassauer et al., 2014).

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3. Materials and methods

Landscape architecture is a relatively young academic discipline that incorporates concepts found in ecology, engineering, the social sciences, architecture, and design. Multidisciplinary studies are typical in landscape architecture, and, therefore, the spectrum of methods is wide. The selection of accepted or appropriate methods is discussed regularly. Swaffield and Deming (2011) highlight the importance of transparency and traceability and of adjusting to each situation rather than focusing on normative research methods in closed disciplines. Otherwise, the multifaceted, practice-orientated nature of landscape architecture might disappear.

Swaffield and Deming (2011) propose a classification system for describing research strategies in landscape architecture. They locate different research strategies along two primary axes: their relationship to epistemology and their relationship to theory (Table 4). They claim that this 'classification provides a way to locate current, operational and potential research strategies within landscape architecture' rather than re-inventing in research strategies already used in other disciplines (Swaffield & Deming, 2011, p. 35).

Table 4. A classification of research strategies in landscape architecture (modified after Swaffield and Deming, 2011).

Relationship to theory

Relationship to epistemology

	Inductive	Reflexive	Deductive
Objective	Description	Modelling	Experimentation
Constructive	Classification	Interpretation	Evaluation & Diagnosis
Subjective	Engaged Action	Design Projection	Logical Systems

Following the classification presented in Table 4, this study uses different research strategies to respond to qualitatively different aims and research questions. The set of research strategies used are description, modelling, experimentation, and design projection. These were selected to ensure a multidisciplinary approach to the production of new knowledge that meets the needs of both academia and practitioners in the field of landscape planning, design, and construction.

Although the research strategies and methods utilised in this dissertation are aligned with the multidisciplinary nature of landscape architectural research, some of the methods build upon the author's background in horticulture and environmental sciences. This kind of utilisation of established practices from neighbouring disciplines is also emphasised by Swaffield and Deming (2011) when describing appropriate methods in landscape architecture. Therefore, one outcome of this dissertation is the development of methods that meet the needs of landscape architecture. These methods are a) Experimentation: heavy rain simulations in an experimental field and b) Design projection: detailed development of the practical implementation of research by design.

Table 5 illustrates the research strategies and methods utilised in relation to the overall aims and research questions. This presentation follows the classification of research strategies by Swaffield and Deming (2011), and the numbers after each method refer to the published papers.

Table 5. Methodological strategies and methods used in relation to overall aims and research questions. P1, P2, P3, P4, P5, and P6 refer to published papers presented after the abstract in this dissertation.

Aims	Research questions	Research strategy and methods	Expected results
AIM A: To present the state-of-the-art of private domestic gardens for green infrastructure	RQ 1: What is the role of private domestic gardens in green infrastructure within the framework of sustainability? RQ 2: How is the non-sealed area of Finnish domestic gardens generated on the plot scale?	***Description and classification:*** ○ Review (P1) ○ Document analysis (P2) ○ Case (P3)	Plot-scale characteristics showing the nature of their multifunctionality and surface coverage/soil sealing
AIM B: To develop detail-scale integration between water and vegetation for local conditions	RQ 3: How should the interaction between soil, water, and vegetation be optimised in Finnish private gardens? a) How should this interaction in the form of bioretention be adopted in local practices? b) What are the construction details and criteria for plant selection?	***Modelling and experimenting:*** ○ Modelling and development of prototypes (P5) ○ Field experiments using the prototypes: short interval flooding test (P4) and heavy rain simulation (P5)	Models for soil, water, and vegetation integration in the case of bioretention Data from functioning of prototypes
AIM C: To improve garden-scale GI to enhance up-scaled GI	RQ 4: How can plot-scale GI be improved to enhance GI on the block and neighbourhood scales?	***Design projection:*** ○ Conceptual development of scalability (P1) ○ Research by design (P6)	Identification of the potential benefits of systemic approaches in upper scales.

3.1 Methods for identifying the plot-scale potential for green infrastructure

The first aim was to describe the current state of private plots and was addressed by a literature review in Paper 1 and document analysis in Paper 2. The literature review collected and categorised scientific articles on the function, use, and meaning of private yards and gardens. The articles were selected using the keywords ‘garden’ and ‘yard’ and focusing on definitions of ‘domestic’ and ‘private’. These articles mainly originated from and addressed Europe, the US, and Australia. The set of reviewed articles was analysed based on their main content and re-organised under five main themes. These five themes were then outlined based on their contribution to the schematic pillars of sustainability.

The description of private gardens was further refined by examining the extent of the plots' surface coverage in a selection of Finnish contemporary plot-scale designs through systematic document analysis in paper 2. Different stages in the planning and design process determined the plots' impermeability, which, in turn, defined the extent of permeable surface coverage and, thus, the possible proportion of GI built on open soil-surfaces. Here, a set of garden designs presented in Finnish housing fairs was used as data. The plans were scanned and different covers were measured using a CAD-based software. These designs demonstrated professional designers' views on the fairs' themes, and the fairs provided content that offers visions and ideas for detached home builders in Finland. These fairs were held in Tampere, Jyväskylä, and Hyvinkää and had the same main themes. The common themes were sustainability and the management of stormwater in the context of sustainable construction. The plot layouts and their associated buildings and private gardens illustrate the key characteristics of future detached houses, which are commercially targeted at residents planning to build a detached house. Garden designs were collected from fairs in Tampere in 2012, Hyvinkää in 2013, and Jyväskylä in 2014. These designs (N=63) were used for a document analysis, which measured impervious and pervious surfaces in contemporary Finnish plots and gardens (Figure 17).

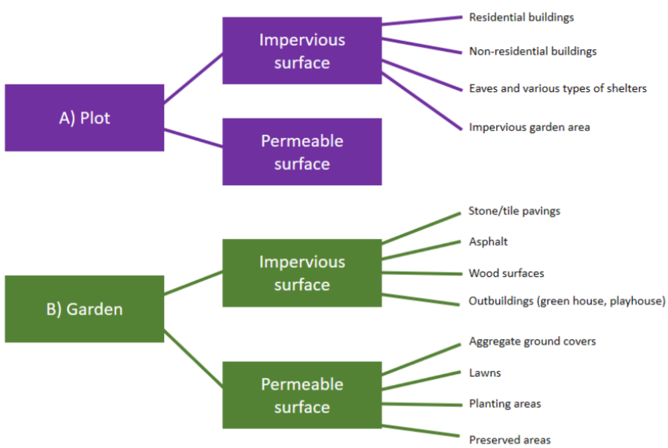

Figure 17. The used classification of pervious and impervious coverage in Finnish single-family plots in paper 2. (Paper 2, Fig. 2)

The document analysis presented some inconsistencies as the size of gardens was not determined directly by subtracting the size of buildings from the plot's size. Garden sizes were measured as the area between the plinth and the plot boundary rather than the area outside the roof in the plot. Thus, the share of eaves and shelters were included in the area of impermeable surfaces even though the garden area and garden-related functions also exist under these shelters and eaves (Figure 18).

Figure 18. The proportions of plot-scale impervious coverage in one of the analysed gardens in Paper 2. Classification is presented in Fig. 17. (Paper 2, Fig. 3)

These two methods provided the backbone to describe the current situation of private gardens, first, in general as a multifunctional platform for GI and, second, in more detail as expressions of different levels of surface coverage. These methods also had constraints. The literature review only produced a general description based on scientific publications, and it seemed that the topic of private gardens was an emerging area of research. The document analysis used garden designs created by professionals, and, therefore, the more typical choices made by owners were not included in this study. Although the choice of designs and their analysis provided a less frequently used dataset to study garden-scale GI, they failed to provide city-specific statistics of LDH and its coverage types.

3.2 Methods for examining detailed bioretention construction

The second aim was to study detail-scale integration of water, soil, and vegetation using the bioretention construction details of Finnish practices as an ideal prototype to understand the mutual relationships. The development of prototypes began with the study of literature presenting optimal construction schemes. First, the construction elements, materials, and functioning were mapped, and then the specific recommendations for cold climates were identified. Based on these findings, a schematic diagram of a bioretention cell was drawn following recommendations from the literature to facilitate its construction, maintenance, and repair in practice. The development of the prototypes required research on and definition of two critical factors: the materials of the growth media and the depth of the total construction of the bioretention cell. These two factors, or variables, became the main focus of the research, and changes in comparable factors drove the definition of prototypes, which were subsequently constructed and tested.

The experiment was performed in two stages, which took place on an outdoor test field. First, a short-interval flooding test was carried out during the growing season of 2015. This identified the plant species that withstood both drought and standing water, which are typical growing conditions in a bioretention cell. The method itself follows the concept of short-interval flooding tests described by Dylewski, Wright, Tilt, and Le Bleu (2011) and Jernigan and Wright (2011). The short-interval flooding experiment provided knowledge on plant species' survival in the conditions of bioretention, but it also provided information on the performance of different growth media as it used a mixture that was in accordance one line of recommendations defined in detail in the bioretention construction literature.

The experimental field was constructed on the Häme University of Applied Sciences' Lepaa campus, 100 km north of Helsinki. It had five cells to compare two different mixtures of growth media and two different construction depths, 80 cm and 120 cm. The bottom size of all cells was 2 x 2 m, and they allowed a ponding depth of 20 cm. The fifth cell was a sand filter without vegetation, which served as a control. Studies for this dissertation included observations of hydrological functioning during the first year after implementation and observation of vegetation coverage during the first two years. Thus, this dataset also included functioning during the first winter and its effects on vegetation. It should be noted that the results here only relate to functioning just after the construction phase and do not relate to other phenomena, such as glogging, or a decline in hydraulic conductivity, which have been reported as common malfunctions.

Cells in the experimental field were located below the surface level and isolated from the surrounding ground to collect all the infiltrated water at the bottom of the construction layers. A drainage pipe installed at the bottom of the cells channelled the infiltrated water to a measuring station that collected discharge (L/s), conductivity (µS/cm), and temperature (°C) data every 10 minutes. However, the surface levelling around the cells prevented natural surface runoff into cells, and, therefore, the quantity of input water was known based on either irrigation or direct precipitation from the nearby weather station. All the bioretention cells had the same vegetation combination and the same plant size.

The functioning of the cells in the experimental field was studied based on three main elements. Hydraulic functioning was studied using heavy rain simulations, which were organised by irrigation repeated at certain intervals and water quantities. This method allowed the simulation of heavy rain conditions even when there was no natural precipitation, and, therefore, the functioning of cells in extreme conditions could be measured. The continuous collection of outflow data also enabled the cells' functioning during winter to be studied. The growth of vegetation was monitored by photographing the surfaces and then measuring the change in green coverage from photographs.

The heavy rain simulation method included six irrigation events. There was one irrigation per day for three consecutive days, and this pattern was repeated during the following week. Natural precipitation was avoided, especially during and just before the first irrigations to ensure non-saturated conditions. The second half of the irrigations generated moist and, later, fully-saturated conditions for simulations to demonstrate changes in infiltration rates. The presentation of these simulations was accommodated to cumulative outflow curves as a function of time. This presentation type had the distinct benefits of a) demonstrating the general graphical outflow pattern; b) providing data to study temporal changes, such as comparisons of lag times and peak flow reduction; and c) providing data to study water quantity observations, such as total volume reduction in saturated and unsaturated conditions.

The research strategy of modelling and experimentation provided an appropriate combination of methods at this stage. The development of construction details and the mixture of growth media did not appear in the methodological choices, although these two stages were crucial in setting up the experiment. Later, these two precise developments proved to be the most essential components for practical operation and commercialisation.

The construction of the entire experimental field consumed a significant portion of the resources for this study, but it will serve as a valuable study environment for future research. The coming years will provide opportunities to monitor and compare the now-established cells as they change while maturing. The disadvantage of the chosen time period for monitoring is clear; however, the investments made during the research for this dissertation allows for further developments in the upcoming years.

3.3 Methods to improve plot-scale green infrastructure by up-scaling

The third aim was to examine how improved GI on the plot scale could improve and support up-scaled GI on the block and neighbourhood scales. The method involved adapting the idea of research by design (RbD), where the researcher is also engaged in the design process (Figure 19). The method explores practical design processes through several iterative and scientific reflective cycles (Roggema, 2016) and systematically combines research inquiry and design thinking (De Jong & Van der Voordt, 2002). The author, as the researcher of this study, performed the analysis, redesigning, and scaling-up. As the main focus was on the improvement of garden-scale GI, RbD was framed to use existing garden designs as a starting point for re-designing the design of the integration of water and vegetation. This limited the garden-scale possibilities but also revealed the practices and challenges involved in moving from the detail to the plot scale. in the design process. The author was educated as a garden designer and had experience in that profession. Hence, this study provides a view of both the general process of garden design and garden designs as a product. This made it possible to achieve the dual outcome of identifying how the design process could be developed and what the outcome might be for different urban planning scales.

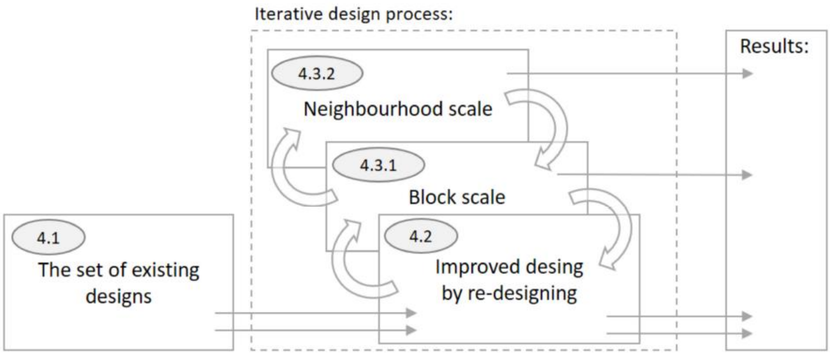

Figure 19. The improvement of plot-scale GI used a method of iterative design process. (Paper 6, Fig. 3)

Here, the RbD incorporated some elements of grounded theory. First, a set of garden designs were systematically analysed to identify how stormwater management practices have been integrated into vegetation and vice versa. The ruslts were coded and grouped to formulate common themes in water and vegetatation integration. This first step provided knowledge of the current situation in garden designs usings designs from the Tampere housing fair in 2012 (N=24). This is one of the fairs examined in the context of impervious coverage on the plot scale. Then, in the second step, the garden designs were re-designed to better integrate stormwater management and vegetation while respecting the form and function of the original designs (Figure 20). This was repeated with all the designs, first on the plot scale and then when scaling the solutions to the block and neighbourhood scales. The outcomes were analysed first by coding and then by categorising them. The main focus was on modifications concerning the integration of water and vegetation. Coding mapped all the main changes in the re-designs. This transformed the information from the drawings into written form. There were 2–8 coded changes or observations per plot related to the design process. These codes were then organised under more general categories that were presented as results from the improved garden designs.

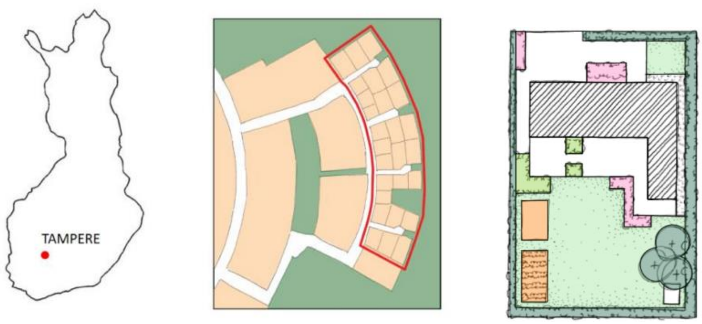

Figure 20. The set of studied garden designs located in Tampere, Vuores. Plots situated between park (indicated in green color) and apartment houses (indicated in brown). An example of the layout of a single plot used in RbD to study the possibilities to enhance the scalable GI. (Paper 6, Fig. 2 and Fig. 4a)

Studying the design process itself provides tools to improve it. However, the methods for examining design processes are not well established. The method of RbD describes the designer's choices during the design process. It does not differentiate between general 'good' and 'bad' choices or evaluate the outcomes compared to general qualities.

4. Major findings

This chapter presents a brief summary of the published papers. The main findings are presented by grouping the results of different papers according to the overall aims of the dissertation (Figure 22): 4.1 corresponds to aim A, 4.2 to aim B, and 4.3 to aim C. A discussion of these findings is presented in Chapter 5.

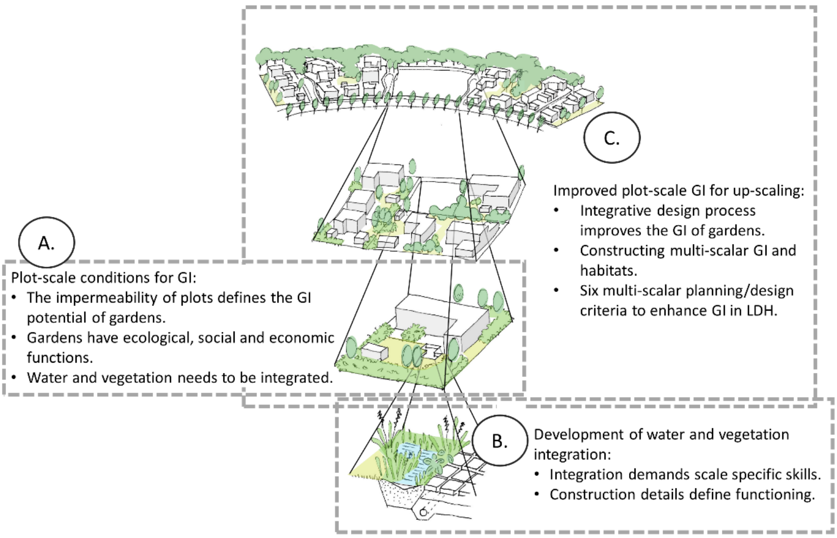

Figure 21. Summary of the key findings in relation to the aims presented in Figure 1. (Figure, O.Tahvonen)

4.1 Plot scale conditions for green infrastructure

4.1.1 The impermeability of plots defines the green infrastructure potential of gardens

While urban planning cannot exhaustively determine the GI of LDH plots, two main planning tools indirectly define ground-connected GI opportunities on the plot scale. The first planning tool relates the plot's housing density and the general allowed layout of buildings and driveways. These factors affect the overall impervious coverage, which, in turn, defines the proportion of the pervious area. Ground-connected GI is located on the pervious proportion of plots; however, some of the pervious areas do not serve GI (Papers 2 and 6). The second planning tool concerns general guidelines and professional practices for plot-scale plantings and vegetation and stormwater management practices (Papers 2 and 5).

Potential areas for plot-specific GI can be determined in progressing steps. After devising a zoning scheme, urban planners begin designing the placement of the buildings on plots. According to Paper 2, design work by architects determines a significant share of the impervious surfaces of a plot, even though the building's indoor floor area, which is the main function of an LDH plot, only covers 62% of the impervious surfaces on the plot. The other shares included covering, pentices and eaves (15%) and garages and related storage spaces (13%). The remaining impervious surfaces (38%) on a plot correspond to outdoor areas, comprising mostly of walkways, parking, and patios (Figure 22).

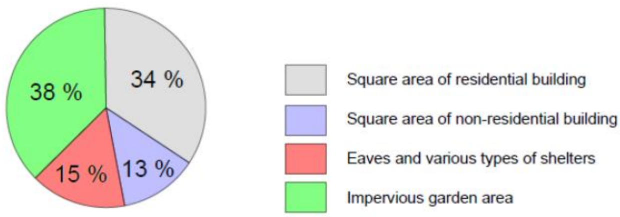

Figure 22. Average impermeable coverage in single-family house plots in three housing fair areas in Finland. (Paper 2, Fig. 7)

Paper 2 also examined the emergence of impervious surfaces on plots of varying density. According to its findings, the architectural designers placed buildings and garages or car sheds according to what was permitted by the zoning scheme and related instructions. In turn, the respective placement of these buildings determined the walkways between the parking area and the building's main entrance. For the sake of assumed amenity, pentices and canopies were included on plots, resulting in sheltered spots in the garden. On the other hand, patios were often located close to the building, adjacent to a secondary entrance to the building's kitchen or living room. These architectural decisions were critical in determining the possibilities for garden design, as well as the impervious surfaces required for the garden design (Figure 23).

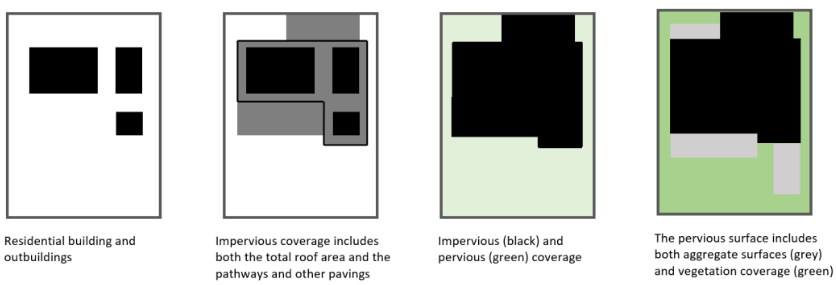

Figure 23. The impermeable coverage includes components from buildings and garden surfaces. However, the actual garden area may continue under eaves and shelters. The extent of ground-connected vegetation follows the area omitted from impermeable surfaces. (Figure, O.Tahvonen)

According to Paper 2, an increase in plot density only results in minor growth in the footprint of residential spaces, while the area of recreational shelters remains nearly unchanged. This means that while the increase in plot density resulted in the construction of housing all or part of which had two floors, the area of pentices and canopies remained the same. Some covering comprised eaves, which contributed to protecting the building's façade, and there was no reason to reduce the area covered by these. However, some of the ground covering related to amenities should be critically considered as, given Finland's climate, spending time outdoors when it rains is not attractive even if the leisure areas are covered.

Plot density did not appear to directly affect the area of impervious surfaces in a garden. In fact, the available space on plots with lower density, i.e. in the category of plot density below 0.2, appeared to produce a wide range of design solutions. Housing density categories based on density rates describe the ratio of planned building volume to the square area of the same plot area. In the category of below 0.2, the total amount of impervious surface in gardens varied between approximately 45 square metres and almost 360 square metres, with an average surface size of slightly over 160 square metres. The largest impervious surfaces were found within the 0.2–0.29 range on the plot density scale, while there was a steady decline in the amount of impervious surface in the gardens of LDH when plot density was higher (i.e. within the categories 0.3–0.39 and over 0.4). Nonetheless, there was considerable variation in the amount of impervious ground covering in gardens across density categories, which served as proof of how garden design can affect the amount of impervious surface on the entire plot..

Conversely, plot density appeared to clearly influence the extent of planting areas, as these areas covered a lower number of square metres once density increased. In the examined density categories, the number of square metres reserved for planting areas was around 200 m^2 in the below 0.2 category and decreased to 75 m^2 in the over 0.39 category. The number of square metres reserved for planting areas can be seen as playing a key role in the GI of an area with LDH as this lays a foundation for multi-layer vegetation, which has been found to play a key role in constructing biodiversity and other ecosystem services. Another factor affecting vegetation is that, along with an increase in plot density, the opportunities for retaining existing vegetation are reduced. According to this study, vegetation areas were no longer retained with a plot density above 0.3.

Residents of LDH plots tend to favour lawns for recreation, as well as for aesthetic purposes. While the use of lawns is based on a cultural tradition and on functional aspects of a garden, lawns are not considered to have a significant ecological value. On the plots included in the study, the number of square metres covered by lawns was reduced along with an increase in plot density as would be expected; however, a plot density of 0.3 emerged as the threshold value for this reduction. On plots with lower density, lawns covered, on average, nearly 250 m^2 while contributing to around 80 m^2 on plots with higher density, although there was considerable variation in the share of lawns between plots.

However, the results indicated that a smaller plot size produced a more sensible scope of lawn areas. Instead of sowing lawns in smaller gardens at random, the placement and extent of the lawns in small gardens were more carefully considered. However, the wide lawn areas on large plots could still be presumed to result from poor planning or a complete lack of planning, which begins by sowing lawn on the entire area and thinking about alternative garden use at a later point in time. Zoning does not typically take a stand on the placement or amount of vegetation in an area, except for individual trees or property boundaries.

Summary: Due to the spatial dimension of the GI concept, the land available for GI in detached housing is highly influenced by plot density and plot layout. In particular, the results of the conducted research reveal that plot density might not directly influence the amount of land covered by roofs but reduces the size of gardens, especially the fraction of pervious and, therefore, vegetated areas. Interestingly, vegetated areas (plantings and lawns) might cover a significant part of those gardens and tend to keep a minimum amount of square metres even when plot densities increase. In general, the proportion of lawns decreases in favour off planting areas as the density increased.

Since GI provides at spatial and biophysical platform for the generation of ecosystem services, including stormwater management (SWM), and for the development of more intense SESs, the findings of this subsection frame the potential of garden-scale GI for the following subsections.

4.1.2 Gardens have ecological, social, and economic functions

The outdoor spaces of LDH plots are considerably multifunctional. Paper 1 reviews a set of articles on gardens to recognise general garden-scale multifunctionality as this provides the background for GI enhancement and for the increase of ecosystem services. Some of the mapped functions and benefits were directly related to GI, while others may only provide the potential for a later reconsideration of mutual functions. Paper 1 identifies 6 main themes or aspects in the set of articles: an anthropocentric approach, a morphological set, property value, surface cover, ecology-related equipment, and vegetation.

From an anthropocentric perspective, gardens have been explored as both physical places as well as as well as arenas for activity involving gardening as a hobby. As environments, gardens produce complex forms of physical and mental well-being for residents. In this context, morphology refers to the size and shape of the garden or its division into a front and back yard. Plots have also been examined in terms of their commercial value. Studies have also explored the possibilities for food production on plots. Most of the available research addressed surface cover, with a focus on examining the formation of impervious surfaces and their effects on stormwater, as well as land-cover richness. Previous studies investigating ecological significance have involved measuring the extent of vegetation-covered areas. Ecological aspects were also examined based on the number of separate and transferable additional elements, such as nest boxes or SUDSs, as well as by determining the vegetation included on plots. The previous studies on vegetation were conducted by defining the floor area, based on the multitude of species, and by measuring the three-dimensionality of plant stands (Paper 1).

The variety of functions of the gardens of LDH plots have considerable potential for urban planning as knowledge of the details on the plots would enable the production of some of a city's ecosystem services on private plots. However, LDH plots and their gardens are prone to change. Increasing the density of housing and, specifically, infill construction reduces garden sizes, which means that careful redesign is required. In fact, enhancing the density of an LDH area in the interest of sustainable development does not always result in overall sustainability as it appears that some ecological processes are hindered, and residents of these areas might be more likely to take overnight trips for recreational purposes and own a second home (Paper 1).

Summary: Domestic private gardens may be interpreted as small SESs. These SESs can be studied with a human-centred approach that can be connected to the concept of ecosystem services, which are highly influenced by the morphological or design qualities of the garden. This approach also highlights the economic dimension of gardens (e.g. property value) and its ecological and performative dimension, which is highly determined by surface cover, ecology-related equipment, and vegetation, which, in turn, influences the water cycle, SWM and the potential use of SUDSs. The complex set of resident's choices and activities constantly modifies gardens either improves or weakens the functioning of ecosystem servises and stormwater performance.

4.1.3 Water and vegetation need to be integrated

In the urban context, the integration of water and vegetation is both a significant potential for GI and a risk for technical constructions. The integration of water and vegetation allows multifunctionality and, therefore, the efficient use of space, but stresses discipline-specific approaches that have a strong background of focusing only on one of the elements. Traditional construction engineering may have aimed to drain and protect foundations from moisture and frost, whereas agricultural biomass production has focused on ensuring continuous water availability in the soil to meet the needs of plant growth. Paper 3 defined these two clearly distinct approaches to water, which have gradually emerged in urban stormwater management. However, as urbanisation has progressed, these two professional perspectives have come into contact as there has the need arisen to assess the condition of water bodies as receiving streams of stormwater drainage systems in increasingly densely built areas. It is clear that there is a need for joint tools, indicators, and concepts to foster the development of joint interest and discussion (Paper 3).

Similar differences in professional perspectives have also emerged in the context of urban vegetation, particularly between the different scales of urban planning. Conservation ecology perceives urban vegetation as shrinking patches and corridors that are losing their continuity in places where vegetation has primarily consisted of a forest area that was on the site prior to construction. By contrast, the horticultural view of urban vegetation is based on constructed, planted, and managed planting areas and trees in parks, along streets, and on plots. Despite this dichotomy, increasingly dense cities must, nonetheless, be able to examine vegetation as an entity, including both of the aforementioned components in a complementary interaction. Such a balanced approach requires examining the topic from the perspective of cities and neighbourhoods, as well as the characteristics of an individual growth site and its ecological potential, which affects the former (Paper 6).

Water and vegetation are interlinked through a slightly less visible factor: urban planning. Specifically, impervious surfaces prevent water infiltration into the ground, resulting in stormwater. However, these impervious surfaces also prevent the development of vegetation on the ground as sealed surfaces prevent light and nutrients from entering the ground surface and restrict microbiological life in the soil. Moreover, impervious surfaces cause stormwater and prevent the growth of plants in the ground. As a result, areas where more water is accumulated emerge along the sides of the impervious surfaces if runoff is directed to these areas. A heavy rain event will result in excessive water and flooding, although with light rain, impervious surfaces may significantly contribute to collecting water for plants (Paper 6). Therefore, impervious surfaces cannot be perceived as simply 'good' or 'bad' but might contribute to the generation of favourable growing environments on a plot without a particular value judgement. This means that, in an urban environment, impervious surfaces and vegetation are interconnected and form a green-grey continuum whose parts cannot be examined as disconnected elements but might be designed together to provide mutual benefits.

Plot-scale conditions for water, soil, and vegetation identified in Paper 2 and Paper 6 are summarised in Figure 24. It demonstrates the polarity of the plot constructions with regard to soil qualities and hydrological conditions. Here, the demand for different kinds of plantings is based on the results presented in Paper 6, which were generated from a set of 27 housing fair gardens in Tampere, Finland.

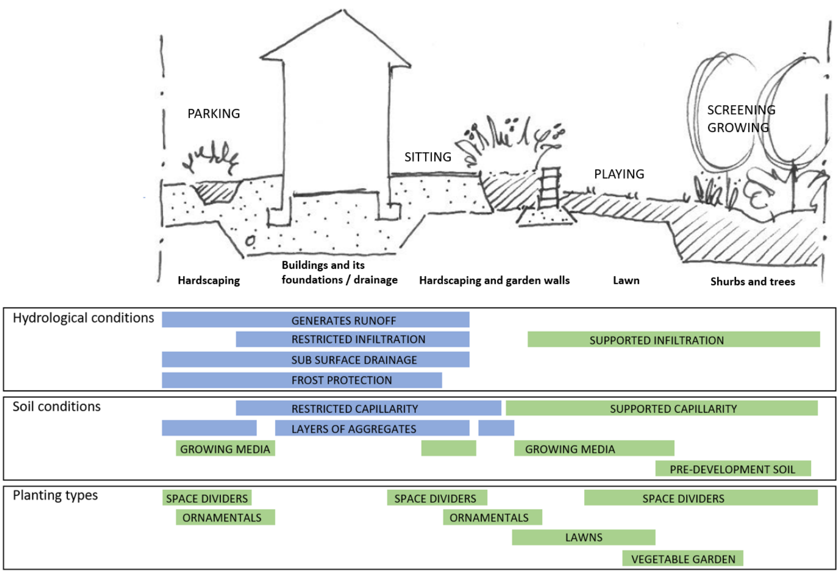

Figure 24. Plot-scale conditions and objectives for managing soil, water, and vegetation during the implementation phase. The figure integrates knowledge from Paper 2 and Paper 6. (Figure, O.Tahvonen)

Sustainable urban drainage systems initially appear to make it possible to bring (storm)water and vegetation together. The most recent descriptions of SUDSs have emphasised the simultaneous implementation of four factors in the multifunctionality of stormwater structures: managing the volume and quality of stormwater, increasing biodiversity, and creating comfort for users. However, vegetation only plays a key role in some SUDSs. Paper 3 identifies differences between stormwater planning based on drying technology and that based on vegetation. This work reveals that water is regarded rather differently in these environments. Thus, one perceives water as a key growth factor, in which case, the design of the growing site aims at improving the ground's water retention capacity while ensuring that the ground will dry between rains so that plants will not be drowned by water standing in the macropores of the soil. However, drying technologies support the downward movement of groundwater and prevent capillary action to keep the foundation of constructions dry. This duality of approaches and, particularly, in the order of their use in the education of urban planners and designers, determine the vocabulary used by those designing the applied solutions, as well as their general approach to achieving the main objective of stormwater management.

Moreover, stormwater management may also have been considered to consist of a standard list of SUDSs. Sustainable urban drainage systems may have been placed on plots as isolated elements without any integration with conventional garden functions or without any systemic meaning, in which case, these mostly correspond to retrofitted decorative features or the replacement of single inlets in designs. In the context of the Vuores neighbourhood (Papers 3 and 6), vegetation integration was not clearly used as part of SUDS; instead, stormwater management was either based on distinct processing systems (end of pipe) or combinations thereof. The selected SUDS favoured visible water in hard elements, for example, in gutters and tanks, in which case, joining vegetation to the structures did not serve a specific purpose.

As explained before, planted vegetation and pervious areas can play a crucial role in SWM, which can be increased by the smart combination of soil, water, and vegetation and with the support of SUDS. Water cycles are normally included as a regulating and supporting ecosystem services, the provisioning of which can be increased through the design and use of SUDSs. Water is at the core of the functioning of many ecosystem services. Therefore, sustainable SWM in general and the systemic use of SUDSs in particular can generate synergies between social and ecological systems as SESs on the plot scale.

Moreover, since water works in a systemic way, this suggests a need for a systemic way of working with SWM and SUDSs as well. It is not enough merely to distribute SUDS on the plot. If water is to be managed as a multi-scalar system, SWM and the use of SUDSs on the plot scale should be defined in relation to garden-specific functions and to other scales: micro scales, such as bioretention, and macro scales, such as neighbourhood or city.

4.2 The development of vegetation-integrated stormwater management through bioretention

To improve plot-scale GI and the provisioning of ecosystem services, the functioning of details needs to be ensured. This connection between the detail and plot scale was achieved by examining and experimenting with bioretention cells. Bioretention is an SUDS that integrates water, vegetation, and soil, and, therefore, includes the elements of GI's core system (Figure 9). However, the guidelines for bioretention constructions are numerous. To address the need for local adaptation of bioretention construction details, Paper 5 presented the development work on bioretention, first, through the literature-based development of details for bioretention construction layers and, in Papers 4 and 5, through the specifications for growth media. The development work included experiments on the functioning of two soil mixtures and construction depths on the mesocosm scale in the test field. The development of the vegetation combination is presented in Papers 4 and 5.

4.2.1 Integration demands the development of construction details

The development of construction details aimed to provide a scheme that incorporates local construction practices and utilises local materials. This led to a single-filter structure using as few layers as possible to be implemented and supervised in practice and to be repaired in the future. It is practically impossible to repair a structure consisting of 10 cm thick layers (e.g. after cable- or wire-installation work), although these layer combinations seem to function fine in laboratory tests.

Construction layers

The proposed construction of bioretention was a single-filter construction (Figure 24), which combines layers of filtering and growth media (hereinafter referred to as growth media). This allowed the provision of more available soil volume for root systems than was achievable with separate layers of sand filters. Despite the aim of avoiding separate transition layers, one transition layer was included in this structure type to separate the growth media and filtration layer from a drainage layer. In some contexts, the transition layer can be replaced by filtering with textile material; however, in this type of SUDSs, the use of these materials is considered questionable as they can become clogged and are difficult to replace. The structure presented in Paper 5 did not include geotextiles.

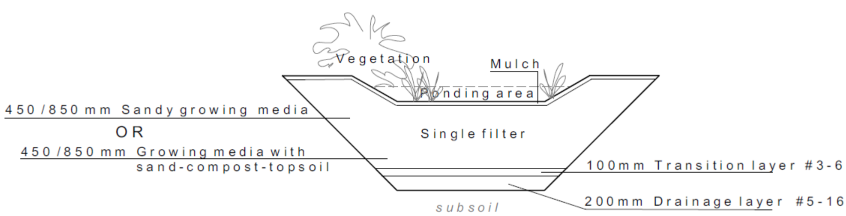

Figure 25. Single-filter layer construction details combining a filter and growth media layer. (Paper 5, Fig. 3)

The adaptation of the structure resulted in the construction shown in Figure 25. In this structure, the first layer from top to bottom consisted of vegetation and a ponding area. The ponding area and its volume were part of stormwater retention strategy, the purpose of which was to delay peak flow. This experiment used a maximum ponding depth of 20 cm as the weight of thicker water layers would have led to unnecessary compression in the lower soil layers, thus reducing their pore volume. The ground surface was covered by an organic mulch layer with the purpose of both reducing weed growth and supporting microbiological functions and regulating moisture conditions in the surface layer.

The layer of growth media was identified as the key material of this structure, and its development process is presented in a separate section. This layer combined two opposite aims set for the functions of this structure: hydraulic conductivity and water retention capacity. The materials sought for the aggregate at the bottom of the structure included soil materials generally available for construction sites. These were screened based on the Finnish sieving criteria for determining grain size distribution. Crushed stones and gravels (i.e. aggregates) are typically readily available. The transition layer in this structure included chipping with a grain size of 3–6 mm, which is commonly used as gritting material and in a 5–15 mm drainage layer, which corresponds to the typical grain size of chipping used for drainage. Drainage chipping was used to fill the surroundings of all subsurface drains.

According to the literature review, there was no unambiguous definition for the total depth of the structure and, therefore, the strengths of the different layers. Thus, this study compared two different total depths at the test site. A low structure may end up above the growing ice layer and, therefore, be subject to freezing. However, deeper structures require considerable land mass relocation, which may pose challenges in practical implementation as groundwater is relatively close to the soil surface in many places in Finland. Therefore, low structures reduce the need for moving moving land masses. In addition, water conductivity may be retained if the frost heaving type is porous or granular in a frozen layer. This is facilitated by the use of coarse soil textures, which reduce the amount of time it takes for water to absorb into the deeper layers and prevents it from freezing.

Growing media

Papers 4 and 5 involved developing the layer of growth media. A short-interval flooding test was carried out in 2015, which involved determining the success of different plant species in various humidity conditions (Paper 4). While the main emphasis was on plant species, this test using a particular growth media served as a preliminary study of the construction of a test site and the initial phase of iterative product development.

A growth media mixture was developed for the short-interval flooding test in collaboration with a local soil material supplier (Figure 22). This initial version had high sand content. In the short-interval flooding test, plants, particularly those with large crowns, were incapable of staying anchored in the growth media as the movement caused by wind during the period of standing water was so considerable that the plantlets could not take root in the medium. The mixture used in the initial phase was developed for the following implementation by adding fine aggregate. However, its share was kept below 5% in compliance with general guidelines. The grain-size distribution of the sandy growth media is presented as a cohesive blue line in Figure 26.

The OM in this sandy growth media was constructed of decomposed tree bark, which is a commonly used component in a growth media mix sold in Finland as it does not include peat and thus adheres to the general Central European guidelines for conserving peatland habitat. In addition, decomposed tree bark was considered to bring more biological activity to the mixture compared to peat. As a result, the decomposed tree bark served as a kind of a microbiological 'starter' in the mixture.

The guidelines on the growth media layer for bioretention also used more broadly interpreted instructions, based on which, the layer comprised a mixture of sand, compost, and local topsoil. No previous comparative studies have been conducted on the functionality of these two clearly distinct growth media; however, both of these types are recommended for bioretention.

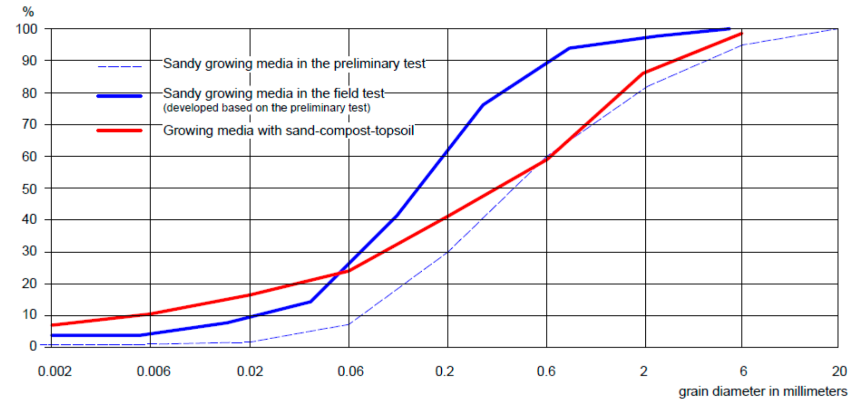

Figure 26. Grain-size distribution of the sandy growth media in the preliminary test (the blue dotted line) and at the field test site (blue line). The other type of recommended growth media contained a mixture of sand, compost, and local topsoil (red line). Sandy growth media included 2.2% OM by mass and the sand-compost-topsoil included 5.3% OM by mass. (Paper 5, Fig. 4)

Vegetation

The plant selection was developed in two different phases. The initial phase involved carrying out a short-interval flooding test for one growing season. The test included determining how well 15 different plant species coped with varying conditions (Paper 4). The second phase involved specifying the selection of plants and following the development as vegetation cover. Therefore, monitoring conducted during the second phase examined vegetation as a whole instead of the success of individual plant species (Paper 5).

Sustainable, frequently available species commonly used in a built environment were selected for the preliminary test. The purpose of this criterion was not to overlook the significance of native plants but to ensure the success of the plant species in an urban environment. When selecting plants, it was ensured that the individual plants could be combined to construct a multi-layer plant community to serve as a design element and support biodiversity.

According to the results of the short-interval flooding test, *Geranium macrorrhizum, Ribes glandulosum* and *Ribes alpinum* could not withstand cyclic humidity conditions, and based on this study, they should not be used in bioretention. The results for *Acer platanoides*, *Sorbaria sorbifolia,* and *Syringa vulgaris* demonstrated weak growth in the most extreme conditions; however, their usability depends on the allowed periods of standing water. The poor success of *Ribes alpinum* came as a surprise as it is generally considered to thrive in both moist and dry conditions. Based on this experiment, the plant is incapable of withstanding constantly changing humidity conditions even if it does well in one of the extreme conditions.

Individual plant species that flourished in the conditions included *Alnus glutinosa, Iris pseudocorus, Betula pubescens, Cornus alba 'Coughaultii', Salix purpurea 'Gracilis',* and *Rhododendron canadense*. The results indicate that some species suffered more from the dry periods than from being left in standing water. Based on changes in their size index, these species included *Rhododendron canadense, Iris pseudocorus* and, most clearly, *Lythrum salicaria,* which demonstrated a more than a two-fold change in its size index in the most extreme conditions (6 days standing water + 6 days without irrigation) compared to moderately extreme conditions (3 days standing water + 6 days without irrigation). Based on the short-interval flooding test, the selection of plant species was adjusted to the needs of the test field. At this point, the selection process involved considering the different strategies plants use to spread to allow the vegetation in the construction to also develop as a dynamic plant community.

The conditions of vegetation-covered SUDSs can vary considerably despite careful planning and measurement calculations. Therefore, there are grounds for constructing planting areas with multiple species that spread appropriately, so other species can replace a species that has declined or died. In the context of plant selection, this means there is a demand for a new kind of competence as there should a mutual balance between the plants in terms of their spreading potential, but the plants should also be able to withstand varying moisture conditions.

4.2.2 Construction details define functioning

For the purposes of examining the water, vegetation, and soil integration, a five-cell test field was constructed with the aim of comparing the functionality of the structure in Finland's conditions. The construction layers of the bioretention cell base on the description in the prevous section, and the surface size of the cells covered an approximately 5 x 5-metre area. The test field had five experimental cells with two construction depths and two growth media mixtures. The fifth cell was a sand filter used to compare the general differences between vegetation-covered bioretention structures and a sand filter. The results of this section are presented in Paper 5.

Heavy-rain simulations

For managing water volumes, the functionality of the test field cells was compared using a heavy rain simulation. The results were used as the basis for evaluating their differences in ponding time, water retention, and peak flow reduction in event-based precipitation. The biggest difference between the materials of the growth media and filter layers was their outflow in the first 8–10 hours as the outflow from the sandy mixture had not even properly begun by the time 70% of the water had already drained from the media-containing compost material. However, in the context of this finding, it must be noted that the results are based on activities in the cells within the first year. At this point, it can be assumed that the soil layers had not yet compacted and settled into their final form.

Ponding time turned out to be an interesting factor in the compared structures as the maximum amount of time a puddle remained visible was 8 hours. However, both international and local instructions determine the maximum time as 24–72 or even 96 hours. It appears that accomplishing such long-term puddling is difficult using the growth media materials included in the comparison. Extending the puddling period over several days would require a considerable increase in the proportion of fine aggregate in the mixtures used.

The outflow pattern between single, repeated simulations revealed the effects of growth media types on outflow speed and volume when rain simulations were repeated on several consecutive days. In the saturated structure, the sandy growing layer mixture worked nearly the same way, whereas the growth media-containing compost proved far more efficient at water retention during the initial days of the rain simulation. Subsequently, its retention capacity changed, but then remained the same for an additional (i.e., third) day. During the first day and the rain simulation days that immediately followed this, the outflow doubled from 175 litres to 350 litres at the 6-hour mark. In contrast, there was no significant change in the lag time as the number of rain simulations increased. Based on the results, it can be noted that, from the perspective of stormwater volume management, the material used in the growth medium and filtering layer is more important than the depth of the structure. Filtering material adjusted to the needs of vegetation cover with grain size and OM content suitable for plants also performs better at managing stormwater volumes compared to a sand filter.

Vegetation coverage

All bioretention cells had the same plant selection, but the plants were pre-grown in the specific soil mixtures in the test field. There were distinct differences in vegetation coverage between the growth media mixtures. However, the depth of the growth media appeared to have no impact on the vegetation coverage.

The general objective of this test field was to provide comparable information regarding vegetation-covered SUDSs and traditional sand filters. This objective demanded fostering plant growth to the appropriate level in terms of multi-layered urban vegetation, and therefore, the aim of maintenance during these first few years was to ensure proper growth in all the bioretention cells. The growth of the vegetation in the sandy growth media had to be already supported by additional fertiliser during the first growing period to achieve growth characteristic of the species. This may conflict with stormwater quality management where the role of bioretention cells is considered to involve filtering out excess nutrients from stormwater. Nevertheless, the starting point for the test setting was to also examine the biofiltering structure as a design element, which makes facilitating multi-layer and vital growth a fundamental premise. Additionally, all of the plants in this experiment were small plantlets.

For the purposes of this study, vegetation coverage and related changes were followed for two growing seasons to make the effect of winter visible. The intention was to follow good gardening practices by fertilising the plants but avoid overfertilisation to prevent unnecessary nutrient emissions from being released in the outflow. Finding such a balance between the nutrients vital to plants and the quality of stormwater emitted from the cell is one of the key differences between the practical context and academic research. While the aim of bioretention is to retain nutrients as efficiently as possible, vegetation growth may not be of secondary importance, particularly in an urban environment. The sandy growth medium used in this experiment appears to be vulnerable to trampling; thus, ordinary urban living may easily prevent the vegetation in the cell from growing. The surface of the bioretention may also be mixed as a result of exposure to children's play, dog-walking, and shortcuts made in everyday walking, and thick and multi-layer vegetation plays a key role in guiding people's movement.

After planting the seedlings, the growth and development of the green coverage was uniform for approximately one month, followed by green coverage forming more rapidly in the cells using the compost mixture. Although the sandy growth media cells were fertilised in accordance with good gardening practices at this stage, their green coverage did not start developing at the same rate as in the areas where compost was used before the autumn. Hence, the initial situation for the two different growth media was different at the beginning of the second spring. In early summer, the green coverage of the areas with media containing compost was 70–80%, and it was approximately 25% in the cells with sandy growth media. However, it must be noted that good gardening practices resulted in an approximately 80% increase in green coverage at the end of the summer, following by 100% coverage in the cells using compost. In the cells with sandy growth media, 100% green coverage was not accomplished during the examination period.

Functioning in cold conditions

While there was lower than average rainfall during the winter following the implementation, the winter period included two separate thawing periods at the end of November and December. Overall, the sand filter appeared to work throughout the entire winter season. The outflow from all of the cells began before the snow coverage melted, as soon as the temperatures climbed above zero. While there was outflow from all of the cells during the initial melting period that occurred in the winter, only the sand filter was clearly working during the second melting period. Nonetheless, no plants were observed to have died because of frost heave in any of the cells during the following growth period. These results concerning activities occurring during the winter describe the functions of individual cells on a mesocosm scale during an individual winter. The results in this area are mostly indicative descriptions of the differences between the cells during the first winter after their construction.

Summary: The field experiment provided a deeper, empirical and scientific understanding of bioretention, particularly, but also of the functioning of the GI's core system. The cells used a single-filter structure and the main comparison was between growth media specifications and construction depths. The construction depth seemed not to have an effect on vegetation coverage, although the growth media used did. Organic matter and fines are needed for water- and nutrient-holding capacity and, therefore, these qualities supported vegetation growth. If plant growth is not the main aim of bioretention design, the sandy growth media seemed to be more suitable for stormwater quantity and quality management. Although these results were developed in the context of bioretention, they also apply to the system of water, vegetation, and soil as GI's core system.

The results are useful for the optimisation of bioretention cells in Finland, the optimisation of substrates, plant selection purposes and, in general, the improvement of GI's core system in Nordic environments. The outcome of this experiment stresses the need for a case and site-specific adaptation of standardised SUDSs and consideration of the design details of the growing conditions of urban vegetation and the ecosystem services it provides.

4.3 Improved plot-scale green infrastructure for up-scaling

If GI and the water system are considered as open systems, integration or consideration of the different scales where these systems are present becomes necessary, especially if the design of plot-scale GI is expected to have a systemic effect, exceeding the aggregation of plot-scale benefits and functions.

4.3.1 The integrative design process improves plot-scale green infrastructure

Paper 6 studied the practical implications of the integration of water and vegetation systems in a design process, first, to improve plot-scale GI and, second, to use the potential of plot-scale GI for enhancement of blocks and neighbourhoods. This section presents the results for how vegetation-integrated stormwater management can be optimised or improved through the design process. Papers 3 and 6 explored how garden designs may include SUDSs and vegetation areas as isolated entities. Soakaways could be placed in the middle of a lawn, even if there was a wide mass planting area next to it. Such design solutions appear to be based on separate thinking processes from those concerning the placement of vegetation and stormwater management. Paper 6 presented an integrative design process, which integrated the regular uses of vegetation in a garden with the goal of balanced stormwater management (Figure 27).

The steps of an integrative design process at plot scale		The main objective
1.	Sketch space and form.	Multifunctional nature of domestic private gardens by conventional design practices.
2.	Identify required planting types.	Mapping the locations and types of plantings in relation to built-up structures and surfaces.
3.	Use SW treatment trains to utilize planting areas.	SWM integration to conventional plantings in several locations of treatment trains.
4.	Design details by adapting the GI's core system to its full extent.	Detailed consideration of water, vegetation, and soil to fullfill plantings/SUDS primary function.

Figure 27. The steps of an integrative design process and the main objectives of each step. (Summarized from Paper 6)

Hence, the integrative design process did not start with determining the stormwater management treatment train but, instead, involved giving shape to the conventional garden design process, the mutual placement and dimensions of different functions, and the divisions and series of spaces. This conventional garden design approach was adopted because LDH gardens include a vast variety of different functions, needs, and locally varying conditions (Paper 1), which must be respected when integrating GI into them. At this stage, which involves determining the design layout and spatial structure, vegetation is simply used as one of the design elements, which does not dominate other design elements.

During the second stage, vegetation on the plot is examined through different planting types in an integrative design. According to Paper 6, five different planting types were identified on studied LDH plots: a) screening and border fences, b) inner space dividers, c) ornamental plantings and decorations, d) vegetable gardens and greenhouses, and e) lawns. Of these planting types, b) and c) required revising the growth media volume as they were located at the concavity of the impervious surfaces draining their environments. In addition to checking the growth media volume, this second design phase also included checking and redesigning the location of planting types b), c), and d) on the plot as the watering of these plant types can be managed with stormwater. In practice, this means examining the appropriateness of the mutual placement of the sites from which stormwater originates and the planting types with a high water demand. Stormwater is generated both at downspouts and at the ends of gutters leading from these, as well as from all level surfaces, such as parking spots, patios, and walkways, and the roofs of garden sheds and greenhouses. However, water needs in these vegetation areas vary; hence, water storage tanks must be placed in these areas to secure a sufficient water supply for a vegetable patch. In contrast, more standard flower beds can benefit from infiltrating stormwater management solutions.

Treatment trains were examined during the third stage. Instead of constructing band-like ditches, the purpose was to utilise the vegetation-covered surfaces as a functional part of the treatment train. The aim was to use the treatment chains to connect the different vegetation areas determined in the previous stage. While it is clear that these chains must be supported by traditional, clearly defined SUDSs, these and the planting areas must together form a chain that does not come across as an end-of-pipe solution. Slightly wider, lush vegetation areas emerged at the lowest points of these solutions on the plots examined in Paper 6. In practice, the stormwater in this area originated from the roof of a building on the other side of the plot and from surfaces used for parking and amenities, where water had to pass through a lawn area used for recreation. Thus, the lawn served as a key management element for conveying and partly filtering stormwater in this block model, although it has not been categorised as a SUDS. Depending on the design solution, similar surfaces that gradually convey and infiltrate water at the same time include perennial flower beds and mass planting areas on the borders of plots and around ramps.

The fourth stage included designing the structure on the detail level to find a balance between water management and the potential for vegetation to thrive. This balance was sought by detailed definitions of the growth media and the structures directly below and adjacent to the media. This integrative design process combines impervious and pervious areas together to take full advantage of the collected runoff for the use of vegetation. Sustainable urban drainage systems play a supportive role in this integrative design process rather than being the indisputable main components.

As a result of this approach, stormwater management involves finding a balance between different surface materials and functional areas. Hard surfaces can contribute to the collection of stormwater, and the locations of planting areas can be adjusted to ensure that they can utilise the water collected in impervious areas in an appropriate manner. The continuum is visible when examining water movement and storage in the soil surface structure. From this perspective, stormwater management also concerns water infiltration, conveyance, and storage for later or further use at the plot scale.

4.3.2 Constructing multi-scalar GI and habitats in LDH areas

Garden-scale design and locations of plantings form block-scale habitats. The pattern of these habitats together with sealed surfaces form the biophysical platform of LDH. According to paper 6, this platform consists of five habitat types: a dry habitat next to buildings, a dry habitat with screening plantings that depends on irrigation during dry periods, garden vegetation with a high capacity for stormwater management, fertile growing depending on irrigation, and a multi-layered vegetation (Figure 28).

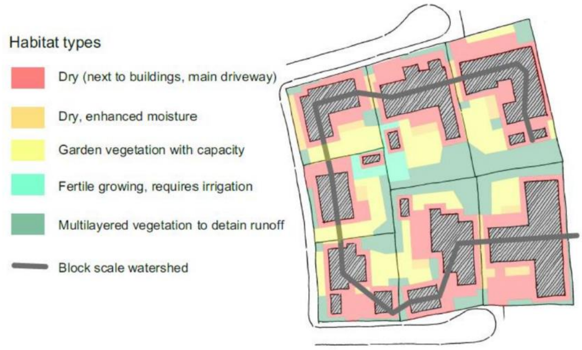

Figure 28. The block-scale habitat types evolving from plot-scale designs.(Paper 6, Fig. 5)

The GI of plots also plays a key role on the block scale and in the entire LDH area. Paper 6 used scaling solutions to the block and neighbourhood scales as a tool for improving GI. When examined on the neighbourhood scale, the green spaces on plots created various habitats, which were based on the aforementioned continua of surface-layer water balance. In the blocks included in Paper 6, the building masses were designed to be placed along the street-side plot borders. As a result, the building masses and their elevations formed a block-specific micro watershed, dividing the plots into a front and back yard. The mutual placement of building masses also determining which parts of the plot were kept dry as a result of building foundation drainage, which also formed a dry, band-like area across the entire block.

This need for drainage with the means of construction technology was also visible on roads, parking areas, and all garden structures protected against frost heave, including walls, pathways, sheds, and greenhouses. These areas had been drained with construction technology solutions and also had to be kept as dry growth sites. This forms the first habitat type for blocks. However, it was noted that a densely built LDH block would inevitably encounter situations where vegetation is planned for these dry areas for various purposes, such as to provide screening on the plot borders and, according to Paper 6, this forms the second habitat type. Paper 6 suggested using shared soil volume in such areas, which involves planting vegetation along the same plot border on neighbouring plots, as this provides the vegetation with more growth media volume than is typically available for vegetation on the plot's borders. This additional volume ensures sufficient water and nutrient retention in the growth media without unnecessary drying caused by the surrounding areas being drained with construction technology solutions. Although this is a dual situation, vegetation often plays an important role in dividing spaces, providing protective screening, and increasing amenity on these spots. Properly planning the growth media factors concerning these areas significantly affects the potential for vegetation to thrive.

Areas of garden vegetation with good capacity formed the third habitat on the block scale. While these areas were located far from the buildings in the examination on the block scale, they were not designed as such for multi-layer vegetation. These areas had the potential for diverse stormwater management and no limitations concerning infiltration. In the neighbourhood investigated in Paper 6, these areas were mainly comprised of lawns or space-dividing planting areas, and this use of space related to stormwater management or planting areas was less dense than in the front yards of the plots.

The fourth habitat type included the areas used for intense growth and cultivation, such as vegetable patches, crate gardening, and greenhouses. These areas, designed for food production, were based on the cultivation of annual food crops, which requires regular irrigation and the availability of nutrients to ensure constant food production. The location of these areas was more random compared to the block-scale habitats described above as not all plots necessarily included cultivated areas. However, in blocks with cultivated areas, there were good grounds for placing these on the same spots on plot borders to ensure an adequate shared growth media volume and optimal light conditions. Cultivated areas need as much unobstructed sunlight as possible. This, in turn, increases evapotranspiration, resulting in higher irrigation needs.

The fifth habitat type consisted of eutrophic multi-layer vegetation, which emerged as separate LDH plots planted with similar vegetation on the corners of plot borders. This creates a shared growth-media volume and a eutrophic, block-specific habitat when the area is located on the lowest point of the block. Working with the growth-media volume shared between neighbours is essential to the formation of all of the above habitat types. Block-specific habitats are fragmented as a result of small, unauthorised solutions, such as the addition of a greenhouse to a vegetable patch. However, overall, a variety of habitats benefits diversity, and developing and appreciating drier habitats on the block scale should, therefore, be emphasised.

Habitats on the block scale, as kinds of meta-planting areas, can further take on a further role on the neighbourhood scale. At this scale, the most eutrophic areas may function as stepping stones joining two separate forest patches or parks or support the corridor-like role of urban green spaces. The watershed presented on the LDH neighbourhood scale helped to bring attention to the blocks and neighbourhoods that can construct eutrophic habitats emerging as a result of the combined effect of stormwater and vegetation. Thus, there are grounds for urban planning on the neighbourhood scale to also determine ecological tasks for plots as these may play a key role as the aforementioned stepping stones or in supporting an ecological network. If LDH plots and their gardens are perceived as mere white zones, the system formed out of them cannot be utilised on the neighbourhood scale. An idea that a neighbourhood could independently gain and manage the tasks of GI on the city scale could be derived from this. If this were achieved, instead of merely randomly producing GI in each plot or block, the neighbourhood would produce it in a predetermined manner, corresponding to an actual need. In this context, the core system would consist of a balance between soil, vegetation, and water on the operative level.

4.3.3 Six criteria to improve the planning and design of scalable GI

Six multi-scalar and hierarchical key criteria (Figure 29) were identified for the design and planning of scalable GI: a) adapting to local conditions (Papers 2, 4, 5, and 6), b) balancing between multiple functions and increasing the provisioning of ecosystem services (Paper 1, 5, and 6), c) controlling imperviousness as a precondition for GI, d) integrating water, soil, and vegetation (Papers 3, 4, 5, and 6), d) maximising the block-scale performance and the proportion of ecosystem services (Papers 1 and 6), and recognising the dynamic character of nature as an asset (Papers 1 and 6).

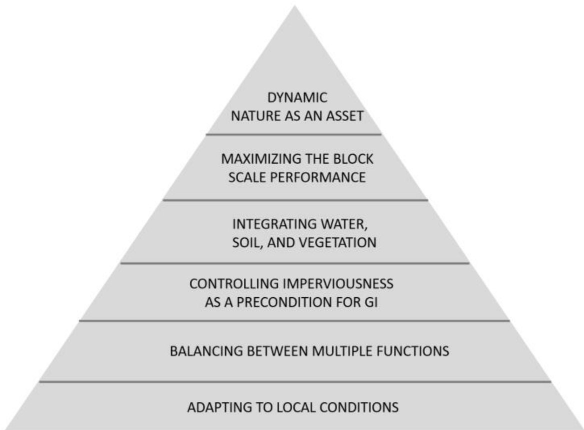

Figure 29. The enhancement of garden-scale and block scale GI builds on six interdependent and hierarchical criteria. (Figure, O.Tahvonen)

The first criterion stresses planning and design practices that **adapt to local conditions.** This criterion entails two approaches, the first of which relates to the site and its location in the landscape ecological system and the conditions it provides for gardens. Second, local adaptation refers to the utilisation of locally-sourced materials in different stages of landscape construction. This perspective emerges from sustainable development goals. It involves making use of the landmass available on the site in construction and improving these for the intended purpose or feature. For stormwater management services, the measurements of the structures must be applied to suit the local rain conditions and the soil's infiltration capacity.

The second criterion concentrates on **balancing between multiple functions** in gardens. The premise is to identify the multifunctional nature of LDH and its gardens as this supports provisioning of ecosystem services. To ensure multifunctionality, Paper 1 presented a checklist for urban planners based on what the dimensions of multifunctionality mean in the context of designing the biophysical environment of gardens. The list brought attention to plot size, the openness of main views, enabling gardening as a hobby with a connection to the subsoil, and the sufficient availability of light as sociotechnical viewpoints. Solutions presented for retaining ecological potential on the plots included restricting the proportion of impervious surfaces, reserving enough space for large trees, and enabling intact growth media layers. The checklist enabled the conditions for multifunctionality to be made more evident to urban planners on the plot scale, which means that the topic was examined from the bottom to the top scale.

In addition, Paper 1 examined scaling the multifunctionality of gardens on the block and neighbourhood scale. Up-scaling aimed to examine what happens to multifunctionality on the higher scales. According to this paper, the size of LDH plots could be compensated for by moving certain garden functions to the block scale. However, caution should be used in predetermining these functions. Paper 1 described this phenomenon as an emergence of system theory, in which the multiple phenomena on a lower scale produce new phenomena at a higher scale. The study described these to include, for instance, the joint ownership or of gardening tools or premises, such as equipment or a specialised greenhouse. In turn, these contributed to laying a foundation that could be utilised in building communality or socioecological sustainability in the LDH area. Therefore, combinations of the different pillars of sustainable development occurring on the neighbourhood scale can also be introduced to the block and plot scales. However, it must be noted that the scaling described in Paper 1 has been carried out from the bottom to the top, and reverse scaling might not produce the same results.

The third criterion is **control over impervious coverage** as the proportion of pervious areas is a precondition for GI. Impervious surfaces limit soil-connected GI potential on the plot scale as impervious surfaces prevent direct water infiltration and separate the soil from vegetation. However, impervious surfaces can have a beneficial effect on the plot scale because they can be used to collect water and convey the resulting surface runoff to vegetation. This can be done if the impervious surfaces on an LDH plot are not extensive, no surface runoff is directed to the plot from outside areas and if the location of the planting areas in relation to the areas from which water originates serves this purpose.

The impervious surfaces on an LDH plot are determined in three stages (as presented in Section 4.1.1): urban planning, architectural design, and garden design, as well as use changes over time. While use change results in changing and reshaping the vegetation areas, it also appears to lead to a gradual increase in impervious areas. These factors form a frame for the selections made in gardens contribute to 38% of the impervious surfaces on plots. This foundation for impervious surfaces in a garden is determined by the locations of the residential building, garage/parking spot, and entryways. When the distances between these are short, the share of paved pathways is smaller. In addition to these factors creating basic functionality on the plot, impervious surfaces emerge as a result of recreational areas, other pathways in the garden, and garden sheds. In itself, gardening also contributes to adding impervious surfaces in LDH gardens. Nevertheless, there are few instructions in urban planning following the currently utilised practices in Finland concerning the generation of impervious surfaces on a plot; instead, the main focus is on determining plot density.

Another factor involved in retaining the GI potential of gardens is control over imperviousness, which is discussed in Paper 2, as impervious surfaces prevent vegetation from connecting to the soil and generate stormwater. The new approach to this equation was based on an examination of the continuum created by different surface materials. A similar approach is also presented in the description of the habitat transect on the block scale. According to Paper 2, plot size did not directly determine the scope of vegetation-covered areas in a garden as green areas were retained even on the most densely built plots. This suggests that living in a detached house is connected to gardening and that people wish to have green areas on their plots regardless of its size. If necessary, residents are even willing to compromise on other impervious surfaces to ensure that their plot includes vegetation coverage.

The fourth criterion is the **integration of vegetation, soil, and stormwater**, which requires knowledge and skills at the detail scale to apply standard SUDSs to local objectives and conditions. From a GI perspective, planning a stormwater management system and vegetation as two distinct entities is problematic because these measures may result in solutions that involve conveying water in a gutter through a planting area suffering from drought. Moreover, strict and partial guidelines and regulations might prevent designers from thinking systemically and holistically. This may, therefore, reduce the opportunities for adapting designs to the local conditions and the availability of soil materials and for optimising soil transfers based on the local mass balance. Standard SUDSs may also guide designers towards designing separate, isolated management solutions. Based on Paper 3, two general professional approaches towards SUDS designs can be identified: promoting the ultimate use of runoff by vegetation or conveying the runoff to outside the plot. The use of runoff for the needs of vegetation is supported by findings on bioretention, both in the case of SUDS and in the areas of conventional plantings.

On the plot scale, developing GI requires an equal, simultaneous design of vegetation and stormwater solutions as part of all other features and functions typically included on a plot. This requires designers to have an ability to adapt and modify their detail-level solutions regarding regular growth media, soil amendments, and infiltration structures. These surfaces and land mass volumes can be used as the basis for managing surface-layer runoff and designing soil structures for water infiltration, storage, and capillary action that are safe for the structures on the plot and available to the roots of vegetation.

In designing GI on the plot level, designers must also examine the entity formed on the **block level** and how independent plots can up-scale to the block, neighbourhood, and city scales. This fifth criterion challenges designers to consider the factors outside the property borders and consider the plot as part of a wider open system and network. The planting areas designed on both sides of borders maximise the volume of growth media. Together, these improve the water- and nutrient-storage capacity of the planting areas and the potential for microbiological activity in the soil and are likely to produce vegetation with more diverse species. Hence, successful designs on the plot scale may contribute to building habitats on the block level. In addition to containing vegetation rich in nutrients and biomass, these habitats can also be dry.

However, in the context of such block-scale habitats, it is worth noting that choices made during the design stage on private plots may be changed as a result of changes to the inhabitants' life stages. Indeed, change and a constant state of transformation are factors intrinsic to an LDH area, which means an improved GI can also be reversed, even within a short period of time. Each LDH has its individual location in the city-scale ecological and functional network, and that affects the potential of the GI that it contains. This location and the dynamic character of nature are a potential asset for urban planning.

The sixth criterion is to enhance garden-scale GI focus on the **dynamic character of nature as an asset**. Ownership entitles people to manage their plots, and owners may even perceive adjustments to their plots as a means of self-expression. Similarly, residents' preferences continue to change, fashion and gardening trends inspire people to constantly modify their gardens, and changes in income level and solutions chosen by neighbours affect the selections made on individual plots. This tendency towards change can also be understood as a positive resource in building sustainability. The constant change in residents' gardens might be studied using the concept of an SES. In practice, managing this change or steering it, at least on some level, requires new tools for urban design and education. Socioecological system management in LDH areas requires participatory workshop activities, a bottom-up approach in cooperation with non-governmental organisations, and various regional development programmes, examples, competitions, events, education, and guidelines. Therefore, maintaining the gardening potential of LDH areas is not only achieved by traditional methods of urban planning since it requires a combination of methods and approaches.

5. Discussion

5.1 Theoretical implications

Urbanisation demands more accurate recognition and use of all urban green spaces. The importance and role of LDH and, in particular, its private domestic gardens have been vague. The overarching aim of this dissertation was, first, to recognise the role of private domestic gardens and, second, to develop their potential to better support city-scale GI in the practices of urban and landscape planning and garden design. A significant proportion of urban residents live in areas of LDH in Finland, and, therefore, the potential of LDH needs to be identified in order for it to be put to better use in urban and landscape planning.

The improvement of garden-scale GI depends on details that integrate water and vegetation through the soil. This dissertation claims that the core system of GI is exactly this interconnected system of water, vegetation, and soil, a claim that is in line with the findings of Pitman and colleagues (Pitman et al., 2015).

When applying this core system to the garden scale, different conditions along the plots that affect the core system's functioning emerge. This causes the core system to modify along the continuum of green and grey, or impervious and pervious surfaces, throughout the garden space. The core system includes both green and gray spaces and exists in all parts of the plot. It exists in planted areas, which provide the vegetation component of GI, and sealed areas, which provide restricted growing conditions but generate water for vegetation. These surface coverages both enable and limit the functioning of different degrees of the GI's core system.

This core system of GI builds on water flows and plant growth, as well as the existence of vegetation and the characteristics of soil as a medium and site-specific regulator. It exists even if the land surface is designed not to have vegetation (e.g. gravel or sand surfaces). In this context, gardeners maintain the land surface and remove vegetation by weeding. A continuous need for weeding indicates that the process of growing exists even though vegetation is removed. In multi-species and multi-layer plantings, the aim of the system is to generate growth, and this objective is supported by horticultural maintenance processes, such as irrigation, plant selection, fertilisation, and soil improvement. At the other end of this continuum is hardscaping, of which the growth of plants is not a goal. Nonetheless, the joints of bricks (on sand bed foundations) create a scarce, dry growth environment for specific plant species. As a whole, this continuum creates a diverse habitat that is apparent in the private gardens of LDH and represents, in most cases, built biodiversity ranging from a building's wall base to the plot's border. The core system of GI modifications is found throughout the surface continuum in private gardens.

This idea of a continuous system also applies to vegetation integrated with buildings, such as green facades and green roofs. In these environments, soil volume and the water-holding capacity of the system are limited. To ensure sufficient conditions for growth, the flows of the core system of GI are supported by external technology and energy (e.g. by drip irrigation, where liquid fertilisers are automatically added). Consequently, this end of the continuum is dependent on technology and energy, while, on the other end, there is planted vegetation connected to the ground with more flexible dimensions of soil volume. In this sense, the continuum implies the degree of the GI's dependency on technology.

Impervious coverage and more detailed surface qualities define the existence of the core system. The idea of a continuum or transect has also been used in earlier publications in the context of GI, such as that by Bartesaghi Koc and colleagues (2017). They identify four categories of GI: tree canopy, green open spaces, green roofs, and vertical greenery systems. The approach to GI as a continuum is also presented by Abunnasr (2012) as GI transects including the land-use forms of peri-urban, suburban, transitional, urban, urban core, and coastal.

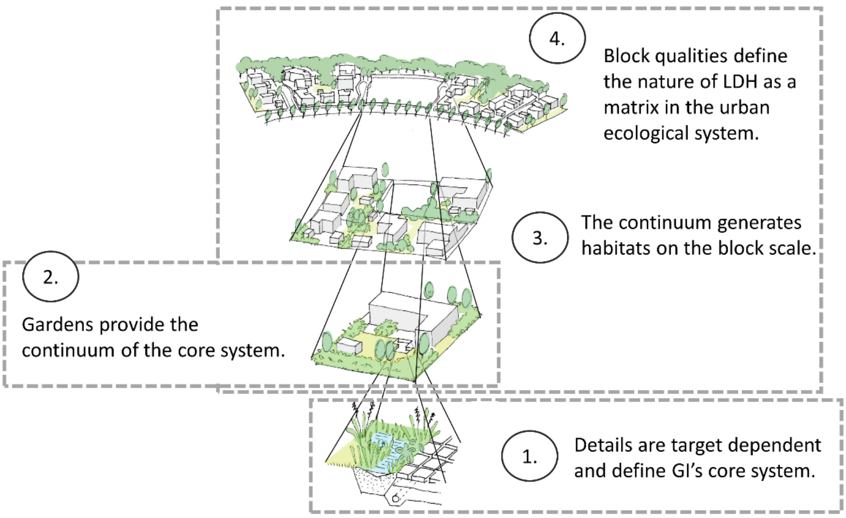

Figure 30. The main outcome of this thesis is the definition of GI's core system and the continuum it builds on plot-scale conditions based on construction practices and possibilities for enhancing GI's core system. In turn, this continuum generates block-scale habitats that define the nature of overall LDH. (Figure, O.Tahvonen)

Green infrastructure's core system constitutes an ongoing process that urban planning, design, and residents modify either purposefully or unintentionally. In addition, the concept of a GI continuum helps both residents and designers consider water, soil, and vegetation as an integral component of GI rather than separate elements of gardens (Figure 30). In this sense, sealed surfaces that are not connected to the stormwater sewage system to collect water for plantings and lawns are one part of a functioning garden-scale GI system. Furthermore, lawns may be considered SUDSs if they receive runoff from nearby paving. The intended purpose of lawns is not stormwater management, but they can infiltrate a significant portion of runoff. Byrne (2007) argues that homogenous lawns do not provide ecologically interesting habitats, but if gardens are considered systems, they do have a clear role in the continuum of GI's core system.

Plot-scale GI also requires the consideration of **changes** that modify the green and grey continuum on plots, garden areas, and surfaces. The uses and needs of residents include the idea of change, and gardening is constantly changing and taking on new forms of gardening. The nature of these multiple ongoing changes throughout LDH areas may be better understood by system thinking. System thinking aims to see the whole instead of separate elements and pays attention to the connections and feedback between separate elements or networks that form the overall system.

Decentralised SWM should not follow mechanistic or reductionist thinking, which only provides a network for water management; rather, it should follow system thinking, which, in the case of LDH, is strongly influenced by residents and gardening preferences in allowed spaces and by the relationships between plots. The plot-scale space is needed for multiple functions, and in the case of gardens, water, soil, and vegetation are only three elements. However, they form the core system of GI, which generates ecosystem services for residents. Therefore, it is the interface between the demand and the provided benefits.

Regarding SWM, system thinking modifies the design process from monofunctional to integrative design. If garden design includes stormwater management as a separate stage, it may result in well-detailed SUDSs, and their capacity may be calculated for water quantity or quality management. At its best, this way of working generates a network of SUDSs that are optimised by careful design but might fail to serve the amenity and biodiversity goals of garden design.

Garden-scale improvement of GI also provides focused possibilities for the block, neighbourhood, and city scales. At the plot scale, GI may be enhanced by following the green-grey continuum; it may also affect habitat provisioning on the block scale and make each LDH work in a specialised way at the city scale. Thus, blocks may support functional vegetation-covered habitats instead of separate plantings.

If McHarg's ecological model is used, urban planning could determine more specialised characteristics for different LDHs, which means ecological functions and aims could be more carefully defined, tutored, and monitored based on an area's location within the landscape's ecological system. In practice, this could imply defining the maximum EIAs to reduce stormwater in the sewage network while also allowing future changes in garden layout, defining the minimum number of trees to increases canopy coverage for the movement and nesting of avian species, and ensuring sufficient garden space to allow multifunctionality to support resilience on the neighbourhood scale.

Private plots of LDH and their constantly evolving gardens form man-made urban nature. It is regenerated by humans who develop a relationship with nature, foster their piece of garden habitat, and express their values or status in their plots. This makes LDH and its gardenscapes diverse and dynamic when considered these from a bottom-up perspective, and this potential could be better included when defining specialised roles for LDH in the planning process (Figure 31). The system of LDH contains rapid, agile changes on the plot and detail scale, but changes are slow and unpredictable on the block and neighbourhood scales, which are typically managed by planners and municipalities. Low-density housing is, therefore, a challenge for the planning and management of GI and its ecosystem services. Urban planning needs to incorporate the bottom-up-based dynamics that may turn the development of GI in any direction and that might have an enormous potential for city-scale GI.

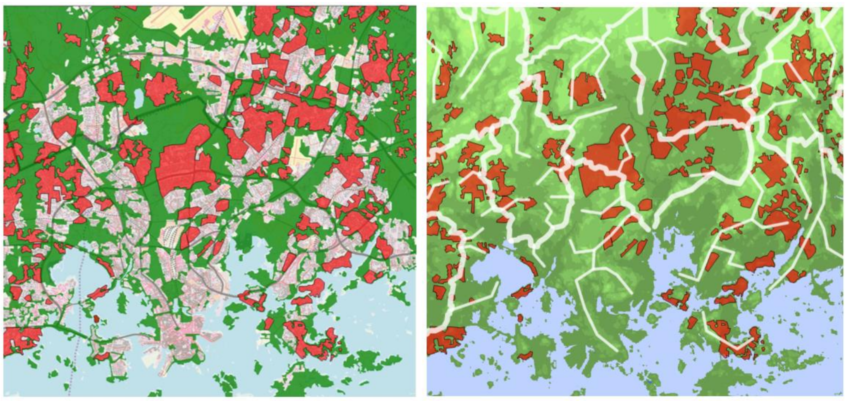

Figure 31. LDH (in red) in relation to public green areas (left); LDH in relation to topography watersheds (right) in Helsinki' metropolitan area. The ecological functions and aims could be more carefully defined when planning focuses on multifunctional and multi-scalar aims for LDH. (Information based on open spatial data)

Low-density housing and its gardenscapes constitute a significant proportion of the urban green space system. This privately owned and managed GI serves ecosystem services not only for its owners but also its citizens. It requires updating planning practices in order to incorporate new methods and tools working on multiple scales, comprehend and incorporate the evidence of change, better define and locate the specific nature that GI holds, and manage and guide grassroots gardeners for specified aims. This provides a basis for novel LDH that evolves from socioecological functioning.

However, urban planning is limited by traditional zoning practices that rely on the correlative placement of functions, which involves determining different functions based on their main purpose. In the context of LDH, the main function is housing, and the most typical metric is population density or square metre floor area. Nonetheless, today's cities include a number of features percolating a number of land-use categories. One of the elements penetrating all land-use categories is urban green spaces. Thus, urban planning faces the challenge of finding representation schemes that cover the multifunctionality of an area, as well as expected changes.

There is a need to present the multifunctional aspects of GI to allow people to properly perceive the nature of GI on the scale of an entire city. Monofunctional urban green space representation schemes usually present areas with LDH as blank areas, although private plots within LDH significantly contribute to the entire city's GI. Low-density housing, as part of the city's entire GI, can serve as a matrix of well-functioning urban ecology systems.

5.2 Practical and methodological implications

This dissertation provides practical implications for urban planners, garden designers, and construction practitioners. For urban and landscape planning, this study formulates two check-lists. The first checklist (Paper 1) relates to the dimensions of multifunctionality in domestic private gardens and aims to link an urban form to the meanings and functions that a garden space provides for its owner. The second checklist (Figure 25) concentrates on enhancing garden-scale GI and its scalability potential.

The improved garden design process provides procedural knowledge for designers. A water-integrated design process should not begin by defining treatment trains or separate SUDSs but by considering the form and function typically found in gardens. If this fundamental meaning of garden design is ignored during the first phase, SWM is not fully integrated into the conventional use of vegetation as space dividers, ornamentals, or border fences. These profound functions of vegetation are then combined with SWM by using, for example, bioretention with multi-layered vegetation. The main consideration is to ensure soil volume that balances water, vegetation, and soil systems in all parts of the garden area, not only within SUDSs.

For urban and landscape planners, this dissertation provides six criteria to enhance multi-scalar planning and design practices. These criteria apply both to garden-scale design and upper-scale planning in LDH. The dynamic nature of LDH and its gardens presents significant ecological potential. This potential may be considered a threat for urban ecology in some cases, but with clever use of still-unknown bottom-up tools, this potential may support also ecological networks.

Alongside the methodological improvement of multi-scalar GI enhancement described above, this dissertation develops construction details and material specifications for the needs of practical landscape construction. For the fields of landscape industries and construction practices, this dissertation provides applicable knowledge for the development of soil mixtures in bioretention and construction details for the use of local materials and for layer depths in managed soils. This knowledge will be further developed over the coming years when data from mature bioretention cells are obtained. Currently, two companies are engaged in product development of appropriate soil mixture and plant type specifications and combinations based on parts of this dissertation.

5.3 Limitations and proposed further research

The focus of this dissertation is private gardens in LDH and scalable GI systems. As this land-use category is heterogeneous and undergoes continuous change, it is challenging to study it fully in this context. However, the generated results describe the multifunctional nature of LDH and reveal the potential for developing scalable GI in LDH areas.

This dissertation uses data from sites in Finland, which restricts the application of the results to local conditions in Finland. This was essential for the development of bioretention practices and, therefore, may be considered one of the advantages of this work. However, the idea of a green-grey continuum can be applied to a wider context.

The research conducted for the dissertation involved triangulation which refers to the use of different methods. The test field provided conventional scientific data regarding the functioning of experimental cells, whereas RbD concentrated on designers' choices during the design process. These methods aimed to map the terrain around vegetation-integrated SWM in practice in an uncommon combination. However, all the data describing private gardens originated from housing fairs. These data describe the 'ideal' designs commercially provided to private homebuilders and are, therefore, not representative of all the Finnish private gardens. These garden designs were created by professional designers who wanted to show possibilities for future homes. The selection of methods and, partly, the development of methods, provides new possibilities for the field of landscape architecture.

Based on this dissertation, there are two main avenues for further research. First, the approach to private gardens and plots as a micro SESs requires further description and research. The set of individual choices and the set of factors affecting these choices should be known in greater detail to develop tools to manage the overall characteristics of plots and LDH areas. This system absorbs and evolves in multiple ways relatively quickly, and this potential could be better used in urban planning. The second avenue involves applying the green-grey continuum concept to other land-use classes. Low-density housing presents heterogeneous surface coverage whereas industrial or car-dependent commercial areas have fewer property owners and, often, more extensive impervious coverage. This raises the question of how the idea of GI's core system and the green-grey continuum would provide enhanced GI in LDH or any other land-use category.

6. Conclusions and Recommendations

This dissertation concentrates on scalable GI in LDH areas and in their associated gardens. Private domestic gardens form the backbone of LDH areas' GI potential. This dissertation recognizes the dynamic system of water, soil, and vegetation as the GI's core system. The functioning of this core system was studied by developing bioretention details for local conditions that provided technical details for the practices of stormwater management but also a more conceptual knowledge on the GI's core system that is essential for the development and management of GI at all scales. The dissertation proposes that garden scale GI may be enhanced by approaching the GI's core system as a continuum to better integrate green and grey components of the urban environment.

The first aim was to investigate the functions and surface coverage of private domestic gardens at plot scale. Gardens have an interconnected set of ecological, economic, and social roles in GI (RQ1). This multifunctional role can support the design and management of gardens and the locations of pervious and impervious areas both during the planning and design phases but also during the on-going choices made by garden owners as part of their maintenance works. This makes of LDH areas and their embedded gardens a specific SES that can either weaken or improve the performance of local GI and the generation of associated ESS.

The impervious coverage of Finnish single-family house plots (RQ2) is determined in urban planning through the definition of housing densities and the locations of buildings; in architectural design through roof size and entrances defining the required passages; and in garden design through the selection of surface materials in the garden area and the design of the garden itself. Increase in housing density decreases pervious coverage that relates to soil connected vegetation coverage. However, the type of vegetation seems to change when housing density increases as the proportion of lawns decreases in favour of plantings.

The interaction between soil, water, and vegetation (RQ3) may be improved by approaching these elements in a more integrative way and by system thinking. Thus, the system integrated by soil, water, and vegetation takes place in all parts of the garden and not only in specially designed constructions such us SUDS. However, specific devises or techniques, such as bioretention, can provide particular solutions for site specific problems such as a more intense management of water. Nevertheless, in all cases, the design of the garden needs to be tailored to benefit local soil and gravel materials, to support vegetation growth, and most importantly perceive the garden as part of a bigger system.

According to these principles, this dissertation argues for the integrative design of stormwater management and plantings at plot scale instead of dividing its design in disconnected phases between uncoordinated specialists.

Moreover, system thinking and the integration of water and vegetation in the garden design process improve scalable GI (RQ4) at garden scale as it recognizes the Core System of GI in all parts of the plot. At garden scale, all types of vegetation should have a role in stormwater management and impervious coverage might act, if adequately designed, as a runoff collector providing water to the plants. This continuum of soil, water and vegetation (Core System of the GI) can also work at a block or neighbourhood scale, supporting the formation of block scale vegetation patches including both dry and more humid microhabitats. These garden scale choices define the up-scaled nature of GI and therefore determinates the performance of LDH areas as part of the urban matrix and their ecological networks. However, the aim of the overall urban GI should be planned, managed, and evaluated in the process of urban planning in order to be effectively supported by private gardens in LDH areas.

The core system takes place along the continuum of impervious and pervious surfaces. Plot-scale design concentrates on this continuum and, for the purpose of enhancing scalable GI, this dissertation proposes an integrative design process to better combine water, vegetation, and soil, and six multi-scalar design and planning criteria for enhancing the potential of LDH areas and their gardens. The concept of GI and its core system can be used to develop the biophysical platform of LDH and its gardens. This biophysical platform then enables cyclic processes, such as water, nutrient, and carbon cycles, that provide ecosystem services. In the case of LDH, residents have an ongoing effect on this system, and the management of this SES in LDH may provide a new and interesting set of research avenues.

References

Abunnasr, Y. F. (2012). Resilient Cities 2. On *Local Sustainability*. (K. Otto-Zimmermann, Ed.), *Resilient Cities 2: Cities and Adaptation to Climate Change-Proceedings of the Global Forum 2011* (Vol. 2). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4223-9

Abunnasr, Y. F. (2013). *Climate Change Adaptation: A Green Infrastructure Planning Framework for Resilient Urban Regions*. University of Massachusetts Amherst. Retrieved from http://scholarworks.umass.edu/open_access_dissertations/775/

Ahern, J. (2007). Green infrastructure for cities: the spatial dimension. *Cities of the Future: Towards Integrated Sustainable Water and Landscape Management. (Ed. VBP Novotny.) IWA Publishing, London,* 267–283. doi:10.1016/0017-9310(88)90092-0

AILA. (2012). Adapting to Climate Change: Green Infrastructure. Retrieved from http://www.greeninfrastructure.org.au/links/default.htm

Allen, W. (2012). ENVIRONMENTAL REVIEWS AND CASE STUDIES: Advancing Green Infrastructure at All Scales: From Landscape to Site. *Environmental Practice*, *14*, 17–25. doi:http://dx.doi.org/10.1017/S1466046611000469

Allen, W. L. (2012). Environmental reviews and cases Advancing Green Infrastructure at All Scales: From Landscape to Site. *Environmental Practice*, *14*, 17–25. doi:http://dx.doi.org/10.1017/S1466046611000469

Arnberger, A. (2012). Urban Densification and Recreational Quality of Public Urban Green Spaces – A Viennese Case Study. *Sustainability (Switzerland)*, *4*, 703–720.

Arnold, C. L., & Gibbons, C. J. (1996). Impervious surface coverage : The emergence of a key environmental indicator. *Journal of the American Planning Association*, *62*(2), 243–258.

Artmann, M. (2014). Institutional efficiency of urban soil sealing management - From raising awareness to better implementation of sustainable development in Germany. *Landscape and Urban Planning*, *131*, 83–95. doi:10.1016/j.landurbplan.2014.07.015

Artmann, M. (2016). Urban gray vs. urban green vs. soil protection — Development of a systemic solution to soil sealing management on the example of Germany. *Environmental Impact Assessment Review*, *59*, 27–42. doi:10.1016/j.eiar.2016.03.004

Askew, L., & McGuirk, P. (2004). Watering the suburbs: distinction, conformity and the suburban garden. *Australian Geographer*, *35*, 17–37.

Bartesaghi Koc, C., Osmond, P., & Peters, A. (2017). Towards a comprehensive green infrastructure typology: a systematic review of approaches, methods and typologies. *Urban Ecosystems*, *20*(1), 15–35. doi:10.1007/s11252-016-0578-5

Benedict, M. A., & Mcmahon, E. T. (2001). Green Infrastructure:, 12–18.

Benedict, M. A., & Mcmahon, E. T. (2006). *Green Infrastructure: Smart Conservation for the 21st Century*. Washington: Island Press.

Bertalanffy, L. von. (1968). *General System Theory Foundation, development, applications*. New York: George Braziller.

Bertalanffy, L. von. (1969). *General Systems Theory - Foundations, Development, Applications*. New York: George Braziller.

Brandt, J., & Vejre, H. (2004). Multifunctional landscapes: motives, concepts and perceptions. In J. Brandt & H. Vejre (Eds.), *Multifunctionals landscapes Volume 1: Theory, Values and History*. Southampton, MA: WIT Press.
Breuste, J. (2011). Summary. In J. Niemelä, J. Breuste, G. Guntenspergen, N. McIntyre, T. Elmqvist, & P. James (Eds.), *Urban Ecology: Patterns, Processes, and Applications* (pp. 71–72). Oxford University Press.
Calvet-Mir, L., March, H., Nordh, H., Pourias, J., & Cakovska, B. (2016). Motivations behind urban gardening: 'Here I feel alive'. In S. Bell, R. Fox-Kämper, N. Keshavarz, M. Benson, S. Caputo, S. Noori, & A. Voigt (Eds.), *Urban Allotment Gardens in Europe* (p. 406). London.
Cameron, R. W. F., Blanuša, T., Taylor, J. E., Salisbury, A., Halstead, A. J., Henricot, B., & Thompson, K. (2012). The domestic garden - Its contribution to urban green infrastructure. *Urban Forestry and Urban Greening*, *11*(2), 129–137. doi:10.1016/j.ufug.2012.01.002
Carlsson, M. K. (2017). Environmental Design, Systems Thinking, and Human Agency: McHarg's Ecological Method and Steinitz and Rogers's Interdisciplinary Education Experiment. *Landscape Journal*, *36*(2), 37–52. doi:10.3368/lj.36.2.37
Charlesworth, S., Warwick, F., & Lashford, C. (2016). Decision-making and sustainable drainage: Design and scale. *Sustainability (Switzerland)*, *8*(8), 1–11. doi:10.3390/su8080782
Colding, J. (2007). 'Ecological land-use complementation' for building resilience in urban ecosystems. *Landscape and Urban Planning*, *81*, 46–55.
Commission, E. (2013). *Green Infrastructure (GI)- Enhancing Europe's Natural Capital*. Brussels. Retrieved from http://ec.europa.eu/environment/nature/ecosystems/docs/green_infrastructures/1_EN_ACT_part1_v5.pdf
Conroy, M. J., Allen, C. R., Peterson, J. T., Pritchard, L., & Moore, C. T. (2003). Landscape change in the Southern Piedmont: Challenges, solutions and uncertainty across scales. *Ecology and Society*, *8*(2). doi:3\rArtn 3
Cook, E. M., Hall, S. J., & Larson, K. L. (2012). *Residential landscapes as social-ecological systems: A synthesis of multi-scalar interactions between people and their home environment*. *Urban Ecosystems* (15). doi:10.1007/s11252-011-0197-0
Davies, C. R., MacFarlane, R., McGloin, C., & Roe, M. (2006). *Green Infrastructure Planning Guide*.
De Jong, T., & Van der Voordt, T. (2002). Criteria for scientific study and design. In T. De Jong & T. Van der Voordt (Eds.), *Ways to Study and Research* (pp. 19–30). Delft: Delft University Press.
Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., … Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, *146*, 107–115. doi:10.1016/j.jenvman.2014.07.025
Dewaelheyns, V. (2013). Garden management and soil fertility in Flemish domestic gardens. *Landscape and Urban Planning*, *116*, 25–35.
Dylewski, K. L., Wright, A. N., Tilt, K. M., & Lebleu, C. (2011). Effects of short interval cyclic flooding on growth and survival of three native shrubs. *HortTechnology*, *21*(4), 461–465.
Eggermont, H., Balian, E., Azevedo, José Manuel N Beumer, V., Brodin, T., Claudet, J., Fady, B., … Lamarque, P. (2015). Nature-based Solutions: New Influence for Environmental Management and Research in Europe Nature-based Solutions, an Emerging Term. *Gaia*, *24*(4), 243–248. doi:10.14512/gaia.24.4.9
Ellis, E. (2015). Ecology is an Anthropogenic Biosphere. *Ecological Monographs*, *85*(3), 287–331. doi:10.1890/14-2274.1
Ellis, J. (2013). Sustainable surface water management and green infrastructure in UK urban catchment planning. *Journal of Environmental Planning and Management*, *56*(1), 24–41.
Ely, M., & Pitman, S. (2014). Green infrastructure: Life support for human habitats. Retrieved from http://www.environment.sa.gov.au/learn/Green_Infrastructure
EPA, E. P. A. (2014). What Is Green Infrastructure? Retrieved from http://water.epa.gov/infrastructure/greeninfrastructure/gi_what.cfm

European Commission. (2012a). Soil sealing, (March). doi:10.1787/9789264202924-graph14-en
European Commission. (2012b). *The Multifunctionality of Green Infrastructure*. *The Multifucntionality of Green Infrastructure*.
European Environment Agency. (2017). *Finland Country fact sheet: land cover 2012*.
Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., … Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, *12*(7), 525–542. doi:10.1080/1573062X.2014.916314
Forman, R. (1995a). *Land mosaics The ecology of landscapes and regions*. Cambridge, UK: Cambridge University Press.
Forman, R. (1995b). Some general principles of landscape and regional ecology. *Landscape Ecology*, *10*(3), 133–142. Retrieved from http://dx.doi.org/10.1007/BF00133027
Forman, R. (2014). *Urban ecology Science of Cities*. New York: Cambridge University Press.
Forman, R., & Godron, M. (1986). *Landscape Ecology*. John Wiley & Sons.
Francis, R., & Chadwick, M. (2013). *Urban Ecosystems: Understanding the Human Environment*. New York: Wiley.
Fuller, R. A., & Gaston, K. J. (2009). The scaling of green space coverage in European cities. *Biology Letters*, *5*(3), 352–355. doi:10.1098/rsbl.2009.0010
Germastani, A., & Benson, M. (2013). A framework for resilience-based covernance of socio-ecological systems. *Ecology and Society*, *18*(1).
Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting cities for climate change: the role of the green infrastructure, *33*(1), 115–133. doi:10.2148/benv.33.1.115
Goddard, M. A., Dougill, A. J., & Benton, T. G. (2010). Scaling up from gardens: biodiversity conservation in urban environments. *Trends in Ecology and Evolution*, *25*(2), 90–98. doi:10.1016/j.tree.2009.07.016
Golden, H. E., & Hoghooghi, N. (2017). Green infrastructure and its catchment-scale effects: an emerging science. *Wiley Interdisciplinary Reviews: Water*, e1254. doi:10.1002/wat2.1254
Green Infrastructure Guidance. (2009). London.
Grove, J., Cadenasso, M., W, B., Pickett, S., Schwarz, K., O'Neil-Dunne, J., … Boone, C. (2006). Data and methods comparing social structure and vegetation structure of urban neighborhoods in Baltimore, Maryland. *Society & Natural Resources*, *19*, 117–136.
Hansen, R., Olafsson, A. S., van der Jagt, A. P. N., Rall, E., & Pauleit, S. (2019). Planning multifunctional green infrastructure for compact cities: What is the state of practice? *Ecological Indicators*, *96*(November 2019), 99–110. doi:10.1016/j.ecolind.2017.09.042
Hansen, R., & Pauleit, S. (2014). From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for Urban Areas. *Ambio*, *43*(4), 516–529. doi:10.1007/s13280-014-0510-2
Harper, G. E., Limmer, M. A., Showalter, W. E., & Burken, J. G. (2015). Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA. *Ecological Engineering*, *78*, 127–133. doi:10.1016/j.ecoleng.2014.06.004
Herzog, C. P. (2016). A multifunctional green infrastructure design to protect and improve native biodiversity in Rio de Janeiro. *Landscape and Ecological Engineering*, *12*(1), 141–150. doi:10.1007/s11355-013-0233-8
Hobbs, R. J., Higgs, E., Hall, C. M., Bridgewater, P., Chapin, F. S., Ellis, E. C., … Yung, L. (2014). Managing the whole landscape: Historical, hybrid, and novel ecosystems. *Frontiers in Ecology and the Environment*, *12*(10), 557–564. doi:10.1890/130300
Ignatieva, M., Stewart, G., & Meurk, C. (2011). Planning and design of ecological networks in urban areas. *Landscape and Ecological Engineering*, *7*, 17–25.
Jalkanen, R., Kajaste, T., Kauppinen, T., Pakkala, P., & Rosengren, C. (2017). *Kaupunkisuunnittelu ja asuminen*. Helsinki: Rakennustieto Oy.

Jernigan, K. J., & Wright, A. N. (2011). Effect of Repeated Short Interval Flooding Events on Root and Shoot Growth of Four Landscape Shrub Taxa. *J. Environ. Hort*, *29*(4), 220–222.
Kambites, C., & Owen, S. (2006). Renewed prospects for green infrastructure planning in the UK. *Planning Practice and Research*, *21*(4), 483–496. doi:10.1080/02697450601173413
Kaupunkisuunnitteluvirasto, H. (2014). Helsingin kestävä viherrakenne Miten turvata kestävä viherrakenne ja kaupunkiluonnon.
Kazmierczak, A., & Carter, J. (2010). *Adaptation to climate change using green and blue infrastructure. A database of case studies*. Manchester.
Kellagher, R., Martin, P., Jefferies, C., Bray, R., Shaffer, P., Wallingford, H. R., … Environment Agency. (2007). *The SUDS manual. Ciria, …*. doi:London C697
Kuusisto-Hjort, P., & Hjort, J. (2013). Land use impacts on trace metal concentrations of suburban stream sediments in the Helsinki region, Finland. *Science of the Total Environment*, *456–457*, 222–230. doi:10.1016/j.scitotenv.2013.03.086
Lähde, E., Khadka, A., Tahvonen, O., & Kokkonen, T. (2019). Can We Really Have It All?—Designing Multifunctionality with Sustainable Urban Drainage System Elements. *Sustainability*, *11*(7), 1854. doi:10.3390/su11071854
Larson, K., Casagrande, D., Harlan, S., & Yabiku, S. (2009). Residents' yard choices and rationalse in a desert city: social priorities, ecological impacts, and decision tradeoffs. *Environmental Management*, *44*, 921–937.
Larson, K. L., Ogden, L., Brumand, J., Polsky, C., Martin, D. G., Harris, E. M., & Garvoille, R. (2012). Heterogeneity in Residential Yard Care: Evidence from Boston, Miami, and Phoenix. *Human Ecology*, *40*(5), 735–749. doi:10.1007/s10745-012-9514-3
Leese, M., & Meisch, S. (2015). Securitising Sustainability? Questioning the 'Water, Energy and Food-Security Nexus'. *Water Alternatives*, *8*(1), 695–709.
Leitao, A., & Ahern, J. (2002). Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape and Urban Planning*, *59*, 65–93.
Liquete, C., Kleeschulte, S., Dige, G., Maes, J., Grizzetti, B., Olah, B., & Zulian, G. (2015). Mapping green infrastructure based on ecosystem services and ecological networks: A Pan-European case study. *Environmental Science and Policy*, *54*, 268–280. doi:10.1016/j.envsci.2015.07.009
Livesley, S. J., McPherson, G. M., & Calfapietra, C. (2016). The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. *Journal of Environment Quality*, *45*(1), 119. doi:10.2134/jeq2015.11.0567
Loram, A., Tratalos, J., Warren, P. H., & Gaston, K. J. (2007). Urban domestic gardens (X): the extent & structure of the resource in five major cities. *Landscape Ecology*, *22*(4), 601–615.
Loram, A., Warren, P. H., & Gaston, K. J. (2008). Urban Domestic Gardens (XIV): The Characteristics of Gardens in Five Cities. *Environmental Management*, *42*, 361–376.
Lundgren Alm, E. (2001). *Stadslandskapets obrokade resurs: om grönstrukturens potential och synliggörande i en hållbar stadsutveckling*. Chalmers University of Technology, Sweden.
Lundgren Alm, E. (2007). Urban Green Structure - a hidden resource. In T. B. U. Press. (Ed.), *Green Structure in Development of the Sustaianble City*.
Lyytimäki, J., Petersen, L. K., Normander, B., & Bezák, P. (2008). Nature as a nuisance? Ecosystem services and disservices to urban lifestyle. *Environmental Sciences*, *5*(3), 161–172. doi:10.1080/15693430802055524
Lyytimäki, J., & Sipilä, M. (2009). Hopping on one leg - The challenge of ecosystem disservices for urban green management. *Urban Forestry and Urban Greening*, *8*(4), 309–315. doi:10.1016/j.ufug.2009.09.003
Marco, A., Dutoit, T., Deschamps-Cottin, M., Mauffrey, J. F., Vennetier, M., & Bertaudière-Montes, V. (2008). Gardens in urbanizing rural areas reveal an unexpected floral diversity related to housing density. *Comptes Rendus - Biologies*, *331*(6), 452–465. doi:10.1016/j.crvi.2008.03.007
Marris, E. (2011). *Rambunctious garden: Saving Nature in a Post-Wild World*. London: Bloomsbury.

Mathieu, R., Freeman, C., & Aryal, J. (2007). Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery. *Landscape and Urban Planning*, *81*(3), 179–192. doi:10.1016/j.landurbplan.2006.11.009

McHarg, I. (1969). *Design with Nature*. (Doubleday & Co, Ed.). New York.

Mell, I. C. (2008). Green Infrstructure : concepts and planning. *FORUM Ejournal*, *8*(March), 69–80. doi:10.1177/0956247806063947

Mell, I. C. (2010). Green infrastructure: concepts, perceptions and its use in spatial planning. Unpublished PhD Thesis, University of Newcastle., (June).

Miller, J. D., Kim, H., Kjeldsen, T. R., Packman, J., Grebby, S., & Dearden, R. (2014). Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology*, *515*, 59–70. doi:10.1016/j.jhydrol.2014.04.011

Nassauer, J. I., Cooper, D. A., Marshall, L. L., Currie, W. S., Hutchins, M., & Brown, D. G. (2014). Parcel size related to household behaviors affecting carbon storage in exurban residential landscapes. *Landscape and Urban Planning*, *129*, 55–64. doi:10.1016/j.landurbplan.2014.05.007

Nations, U. (2018). *Wo r l d U r b a n i z at i o n Pro s p e c t s : The 2018 Revision*.

Ojala, A., Niemelä, J., & Yli-Pelkonen, V. (2017). Impacts of residential infilling on private gardens in the Helsinki Metropolitan Area. In P. Clark, M. Niemi, & C. Nolin (Eds.), *Green Landscapes in the European City, 1750-2010* (pp. 71–86). Routledge.

Opdam, P. (2018). Exploring the role of science in sustainable landscape management. An introduction to the special issue. *Sustainability (Switzerland)*, *10*(2). doi:10.3390/su10020331

Owen, J. (1991). *The Ecology of a Garden: The First Fifteen Years*. Cambridge: Cambridge University Press.

Payne, S., & Barker, A. (2016). Implementing green infrastructure through residential development in the UK. In D. Sinnet, N. Smith, & S. Burgess (Eds.), *Handbook on Green Infrastructure, Planning, Design and Implementation*. Northampton: Edward Elgar publishing.

Peng, L. L. H., & Jim, C. Y. (2013). Green-roof effects on neighborhood microclimate and human thermal sensation. *Energies*, *6*(2), 598–618. doi:10.3390/en6020598

Pitman, S. D., Daniels, C. B., & Ely, M. E. (2015). Green infrastructure as life support: Urban nature and climate change. *Transactions of the Royal Society of South Australia*, *139*(1), 97–112. doi:10.1080/03721426.2015.1035219

Pullin, A., Knight, T., & Watkinson, A. (2009). Linking reductionist science and holistic policy using systematic reviews: unpacking environmental policy questions to construct and evidence-based framework. *Journal of Applied Ecology*, *46*, 970–975.

Redman, C. L., Grove, J. M., & Kuby, L. H. (2004). Integrating social science into the Long-Term Ecological Research (LTER) Network: Social dimensions of ecological change and ecological dimensions of social change. *Ecosystems*, *7*(2), 161–171. doi:10.1007/s10021-003-0215-z

Roggema, R. (2016). Research by Design: Proposition for a Methodological Approach. *Urban Science*, *1*(1), 2. doi:10.3390/urbansci1010002

Roy, A. H., & Shuster, W. D. (2009). Assessing impervious surface connectivity and applications for watershed management. *Journal of the American Water Resources Association*, *45*(1), 198–209. doi:10.1111/j.1752-1688.2008.00271.x

Rudd, H., J, V., & Schaefer, V. (2002). Importance of backyard habitat in a comprehensive biodiversity analysis of urban green spaces. *Restoration Ecology*, *10*, 368–375.

Sack, C. (2013). Landscape architecture in an expanded field. *Ecological Processes*, *2*, 35.

Sandström, U. (2002). Green Infrastructure planning in urban Sweden. *Planning Practice & Research*, *17*, 373–385.

Schneider, D. (1994). *Quantitative Ecology: Spatial and Temporal Scaling*. San Diego: Academic Press.

Schueler, T. (1994). The importance of imperviousness. *Watershed Protection*

Techniques, *1*, 100–111.
Schueler, T., Fraley-McNeal, L., & Cappiella, K. (2009). Is Impervious Cover Still Important? Review of Recent Research. *Journal of Hydrologic Engineering*, *14*(4), 309–315. doi:10.1061/(asce)1084-0699(2009)14:4(309)
Shuster, W., & Rhea, L. (2013). Catchment-scale hydrologic implications of parcel-level stormwater management (Ohio USA). *Journal of Hydrology*, *485*, 177–187. doi:10.1016/j.jhydrol.2012.10.043
Sijtsma, F., de Vries, S., van Hinsberg, A., & Diederiks, J. (2012). Does 'grey' urban living lead to more 'green' holiday nights? A Netherlands Case Study. *Landscape and Urban Planning*, *105*, 250–257.
Sipilä, M., Bäcklund, P., & Tyrväinen, L. (2009). Vaikuttamisen rajoilla. *Alue ja Ympäristö*, *38*(1), 39–50.
Skärbäck, E. (2007). Landscape planning to promote well being: Studies and examples from Sweden. *Environmental Practice*, *9*(3), 206–217. doi:10.1017/S1466046607070299
Smith, R. M., Thompson, K., Hodgson, J., Warren, P., & Gaston, K. (2006). Urban domestic gardens (IX): composition and richness of the vascular plant flora, and implications for native biodiversity. *Biological Conservation*, *129*, 312–322.
Sperling, C. D., & Lortie, C. J. (2010). The importance of urban backgardens on plant and invertebrate recruitment: A field microcosm experiment. *Urban Ecosystems*, *13*(2), 223–235. doi:10.1007/s11252-009-0114-y
Starfinger, H., & Sukopp, H. (1994). Assessment of urban biotopes for nature conservation. In *Landscape planning and ecological networks* (pp. 89–115). Amsterdam: Elsevier.
Stone, B. (2004). Paving over paradise: how land use regulations promote residential imperviousness. *Landscape and Urban Planning*, *69*, 101–113.
Strandell, A., & Hall, M. (2015). Impact of the residential environments on second home use in Finland – Testing the compensation hypothesis. *Landscape and Urban Planning*, *133*, 12–23.
Swaffield, S., & Deming, E. (2011). Research strategies in landscape architecture: mapping the terrain. *Journal of Landscape Architecture*, *6*(1), 34–45.
Tapio, P., & Willamo, R. (2008). Developing interdisciplinary environmental frameworks. *Ambio*, *37*, 125–133.
Tjallingii, S. (2005). Green structure and urban planning, general outcomes of COST Action C11. In A. C. Werquin, B. Duhem, G. Lindholm, B. Oppermann, S. Pauleit, & S. Tjallingii (Eds.), *COST Action C11. Green structure and urban planning. Final report.* (pp. 15–19). Luxemburg.
Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kazmierczak, A., Niemelä, J., & James, P. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landscape and Urban Planning*, *81*(3), 167–178.
Urban Europe. Statistics on cities, towns and suburbs. (2016). Luxembourg.
van Heezik, Y., Freeman, C., Porter, S., & Dickinson, K. (2013). Garden Size, Householder Knowledge, and Socio-Economic Status Influence Plant and Bird Diversity at the Scale of Individual Gardens. *Ecosystems*, *16*, 1442–1454.
Vickery, M. (1995). Gardens: the neglected habitat. In A. Pullin (Ed.), *Ecology and Conservation of Butterflies* (pp. 123–134). Dordrecht: Springer.
Walker, B., & Salt, D. (2006). *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. (I. Press, Ed.). DC.
Wang, J., & Banzhaf, E. (2018). Towards a better understanding of Green Infrastructure: A critical review. *Ecological Indicators*, *85*(September 2017), 758–772. doi:10.1016/j.ecolind.2017.09.018
Weber, T. C., & Allen, W. L. (2010). Beyond on-site mitigation: An integrated, multi-scale approach to environmental mitigation and stewardship for transportation projects. *Landscape and Urban Planning*, *96*(4), 240–256. doi:10.1016/j.landurbplan.2010.04.003
Werner, P. (2011). The ecology of urban areas and their function for species diversity. *Landscape and Ecological Engineering*, *7*, 231–240.
Williams, N. S. G., Lundholm, J., & Scott Macivor, J. (2014). Do green roofs help urban biodiversity conservation? *Journal of Applied Ecology*, *51*(6), 1643–1649.

doi:10.1111/1365-2664.12333
Wright, H. (2011). Understanding green infrastructure: The development of a contested concept in England. *Local Environment*, *16*(10), 1003–1019. doi:10.1080/13549839.2011.631993
Xu, P. (2015). Applying Systems Thinking : Geodesign Structure Provides General Models Integrating Architecture with Landscape Planning and Design to Create a Sustainable Environment. *Proceedings of Digital Landscape Architecture*, 195–204.
Ympäristökeskuksen, S. (n.d.). *Kaupunkiseutujen vihreän infrastruktuurin käsitteitä*. Retrieved from https://helda.helsinki.fi/bitstream/handle/10138/42483/SYKEra_39_2013.pdf?sequence=1&isAllowed=y
Young, C., Jarvis, P., Hooper, I., & Trueman, I. (2009). Young, C., Jarvis, P., Hooper, I. and Trueman, I. (2009) Urban Landscape Ecology and Its Evaluation: a Review. pp.45-69. In A. DuPont and H. Jacobs (eds.) Landscape Ecology Research Trends. Nova Science Publishers: New York. *Landscape Ecology*, 45–69.

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Paper 1

Tahvonen, Outi; Airaksinen, Miimu. 2018. Low Density Housing in Sustainable Urban Planning – Scaling down to private gardens by using the green infrastructure concept. Land Use Policy, 75, 478-485.

Land Use Policy 75 (2018) 478–485

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Low-density housing in sustainable urban planning – Scaling down to private gardens by using the green infrastructure concept

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ARTICLE INFO

Keywords:
Sustainable cities
Densification
Green infrastructure
Multifucntionality
Low density housing
Private gardens
Scaling up

ABSTRACT

Using green infrastructure (GI) concept, urban green spaces in the form of combined private and public green areas with planned and unplanned vegetation, have been recognized as a key element in sustainable solutions for urban communities. For cities, GI provides ecological, social, cultural, technical, and economic functions that also comprise low-density housing (LDH) and its private gardens. LDH can be considered a landscape's ecological matrix that serves as a multifunctional platform for garden-related sociocultural and economic functions. It is composed of technical solutions and processes that reorganize themselves according to residents' ongoing choices. However, the paradigm of sustainable cities argues for the efficient use of space, and LDH may be an inviting area for densification. Infill in LDH increases the number of residents but decreases the space for gardens. Urban planners need to be aware of the potential role of LDH gardens in GI and the pillars of sustainability. This study concentrates on LDH and its gardens in scaling-up approach. First, it reviews some recent studies on domestic private gardens under the pillars of sustainable development and proposes a checklist of sustainable garden characteristics to used by land-use planners. Then it considers possible ways to maintain the multifunctionality of LDH when scaling up to blocks and neighbourhoods.

1. Introduction

Sustainable cities maintain a balance between ecological, economic, and sociocultural pillars. These pillars define planning objectives to facilitate the urban life and residents' well-being, preserve biodiversity, and create economic activity to create jobs, income, and a tax base in cities. Planning for sustainable cities also demands concentration on specific factors such as urban sprawl, energy efficiency, and transportation systems that penetrate all land-use categories by all the sustainability pillars.

Regardless of how sustainability is formulated, there is a demand for practical solutions for sustainable urban planning because urbanization and the world's population continues to increase (United Nations, 2015). After all, cities are considered the most effective solution for transportation, potable water, sanitation services, and electricity (e.g., Wu 2013). Urbanization requires urban planning to determine whether the city sprawls to unbuilt areas or compacts the existing ones. Densification and infill are practical tools used to prevent urban sprawl, and the most effective densification takes place in residential areas that occupy large areas and cover the surface inefficiently.

However, continuous densification decreases the proportion of urban green spaces by reducing both public green areas and private domestic gardens. Some recent studies mention a change in residents' recreational behaviour in densified areas. Arnberger (2012) claims that densification around public green areas might reduce the recreational value of these areas. If a private garden or nearby park cannot provide recreation for residents, they will travel to more distant sites. Sijtsma et al. (2012) found a relationship between the greyness of the living environment and the compensating behaviour of spending more holiday nights away from home. Strandell and Hall (2015) found that a lack of private gardens is related to more intensive use of leisure homes.

Indisputably, urban planning practices need to account for not only the density of residential areas but also other functions that exist there. Residential areas have a diverse system of ecological, economic, and sociocultural microscale functions. This multifunctional scene takes place mainly between the buildings, meaning that if densification and infill are claimed to be a solution for sustainable urban planning, the limits of densification need to be considered in a holistic manner, especially in residential areas.

The challenge for planning practices lies in the conventional nature of these practices that are based on separate land-use categories such as residential, commercial, industrial, and green areas. If urban green

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https://doi.org/10.1016/j.landusepol.2018.04.017
Received 13 June 2017; Received in revised form 7 April 2018; Accepted 8 April 2018

spaces are defined by these categories, only “municipal” green spaces are included. However, “the total urban green” includes all the vegetation in every land use category. Privately-owned green spaces such as private domestic gardens and the greenery of commercial or industrial plots are a considerable proportion of the total green space system. Total urban green can be defined as the concept of green infrastructure (GI).

GI and its multifunctional approach provide a promising frame to assess micro-functions in residential gardens and yards. Multifunctionality in GI is formed from the holistic integration of ecological, economic, and social influences (Mell, 2008). This approach links GI to the pillars of sustainability. Here, the biophysical dimension of GI concerns vegetation as well as the soil, water, and environment that is required for processes that support vegetation growth and the hydrological cycle. Low-density housing (LDH) as a biophysical platform is a combination of garden-scale micro-functions based on complex and dynamic systems of natural processes, sociocultural networks, and communities.

The objective of this study is to identify the multifunctional scene that private gardens provide for low-density housing and define possible ways to retain its multifunctional nature when scaled to blocks or neighbourhoods in planned LDH. Urban planners need to recognize the potential of this scene as they execute in practice the idea of sustainable and compact cities by planning new developments or densifying existing areas. There is a risk that only the housing’s function in residential areas is considered in LDH. This single-function approach neglects cross-cutting functions that are typical premises for contemporary sustainable cities. GI as a representation of the total urban green penetrates all land-use categories.

This study narrows the focus to the biophysical platform of LDH and its gardens to serve as a tangible link to planning practices. This means our approach considers this platform a scene for economic and sociocultural functions and may be unfavourable for them. In terms of ecosystem services, this study concentrates on a biophysical base that provides ecosystem services when functioning properly. However, this approach may exclude some benefits and values (Blicharska et al., 2017).

The following questions need to be answered: What can private domestic gardens in low-density housing contribute to sustainable urban planning in the form of multifunctional green infrastructure? How can these contributory factors be identified in relation to the different sustainability pillars? How can private gardens and low-density housing preserve their multifunctional potential in densification?

2. Materials and methods

We first framed the objective by clarifying the role of the landscape’s ecological background in GI and practices in the planning process that affect GI planning. This part describes the nature of top-down concepts and their relationship to low-density housing in the urban settings. Then we reviewed recent garden-scale studies to identify the functions and elements that occur on the garden scale. This review included scientific articles concerning private domestic gardens and yards that originated mainly in Europe, Northern America, Australia, and New Zealand. These studies do not cover all the publications on garden-scale studies, but they aim to demonstrate the nature of the multiple functions that take place in private gardens. The set of previous studies were first analysed based on their essential contents and then freely organised by common topics. Topics, such as a landcover’s size or richness, arose as the individual studies were grouped together. Then common themes for titles were developed, and all the titles were categorized under these five emerged themes describing individual gardens: anthropocentric, typologies, surface cover, equipment, and vegetation. Finally, the five themes were arranged by their role in contributing to multifunctional GI and sustainable development: sociocultural, economic, and ecological. Lastly, we proposed a checklist for planning practitioners to recognize garden-scale multifuctionality based on the review and discussed the potential of garden-scale qualities to be scaled-up to blocks and neighbourhoods. This part explored possible ways to maintain garden-scale multifunctionality when densification occurs in low-density housing.

3. Urban Green spaces as a component of sustainable city planning

Urbanization causes indisputable changes in a landscape’s physical aspects; however, it also modifies processes involving the landscape such as hydrological systems, biochemical cycles of nutrients and metals, greenhouse gas emissions, and levels of biodiversity in biotic communities (Grimm et al., 2008). Urbanization and land-use changes also generate a new kind of nature (Marris, 2011; Uggla, 2012) and recreate urban-specific habitats like novel and designed ecosystems that are not seen elsewhere.

In sustainable urban planning, it is necessary to combine the built environment and nature into a single entity, where the proportion of green and grey vary and transect through all the different land-use categories. Lindholm (2017) describes this as “green-gray” dichotomy in the context of GI, and she specifically stresses that GI needs to be considered as the entire urban landscape rather than only the public green spaces. Several scientists demand that the polarized man and nature segmentation in the traditional urban land use paradigm be given up. Nature is better understood as socio-environmental arrangements; Cook et al. (2011) describe human-natural systems where multiple social and biophysical processes function on different scales. Naveh (1995) suggests the concept of total human ecosystems where nature and culture interact in a holistic and interdisciplinary way. These studies support considering all urban vegetation (and spaces required to run hydrological processes as well as carbon and nutrient cycles for the growth of vegetation) of man-made, semi-natural, or novel ecosystems in the continuum of urban green spaces.

3.1. Shades of green in the urban context

The widely used “patch-corridor-matrix” (PCM) model developed by Forman and Godron (1986) and Forman (1995) describes the interaction between landscape forms and processes and their relationship to landscape functioning (Francis and Chadwick, 2013). This PCM model represents a landscape pattern in three forms: separated patches, linear corridors, and a matrix as the dominant basic surface. Landscape ecology typically considers patches as places where things live and corridors as connective elements between patches (Matlock and Morgan, 2011). Interest in urban ecology has been focused on patches and corridors, and the outcome of urbanization has been studied from the perspective of habitat loss, fragmentation, and loss of biodiversity (Penteado, 2013). Lately, the urban matrix has become an interesting theme, even if it has been considered the background ecosystem or land-use type (Forman, 1995) or even described with hostility (McGarigal and Cushman, 2002).

The characteristics of an urban matrix are site- and time-specific. In residential areas, the matrix rests on the street grid, private parcels, and the vegetation on them (Ghosh and Head, 2009). The quality of this residential urban matrix differs from industrial or commercial areas because private owners can have a wide range of garden preferences. However, a residential area, as a matrix, provides a major component for GI. The characteristics of urban green spaces in residential areas are based on housing density and the proportion of gardens and permeable (non-sealed) surfaces that allow vegetation growth. Residential areas and their gardens provide a constantly changing urban green that offers a habitat for flora and fauna and the possibility for species movement (Werner, 2011). These new habitats fulfil a function even if they are put to extreme use (Young et al., 2009), but all parts of them might not provide ecological value, such as concrete or asphalt paving and homogenous lawns (Byrne, 2007). The new interest in this broad concept of urban nature has inspired studies where trees, birds, flowerbeds, watercourses and ponds, gardens, and parks are viewed as a representation of urban nature.

The PMC model also provides an approach to GI planning. Gill et al., 2007 claims that separate GI elements build up to create corridors, patches, and a matrix on the city scale, requiring decisions like determining "which type of actions are likely to be most beneficial and in which locations". Additionally, Goddard et al. (2010) claim gardens should not be considered "separate entities at the individual scale, but instead…as interconnected patches or networks of green space acting at multiple spatial scales across the urban landscape". However, GI does not stand as a static planning concept; it challenges planners to consider change and explore ways to enable resilience in different land-use categories.

3.2. Change and multifuctionality in planning practices

In urban planning, sustainability initially focused on concepts aimed at providing stability or control of change because there was a need to control change and growth (Ahern, 2011) or implement technical solutions (Campbell, 1996). The earlier debate focused on either compact and dense areas or decentralization (Uggla, 2012). Recent sustainable concepts in urban planning highlight the resilience (and, therefore, the capacity) of systems to organize and recover from change and disturbances. Forman (1995) described space and time as fundamental dimensions that allow for natural variation and disturbances. The starting point for the planning process and the planner's knowledge is managing and understanding the change and the connection between structure and function and vice versa. Ahern (2011) characterizes transdisciplinary, multiscaled, and multifunctional approaches as typical elements in sustainable urban planning and as the nature of GI planning.

In LDH, resiliency relies on scattered ownership and diversity in the owners' ever-changing interests. In general, LDH forms a flexible green entity based on permeable surfaces and subsoil qualities that allow the existence of garden vegetation and its tree coverage. For resiliency, gardens potentially offer a fresh opening for urban planning. As Ahern (2013) and Ahern et al. (2014) state, the change needs to be planned collaboratively, include the application of local knowledge, and be monitored and analysed after the planning and implementation phases. Otherwise, the learning loop is not closed.

It is not self-evident that change is the main component of sustainable urban planning. Change is gradual and difficult for land-use planners or policymakers to manage (Thompson et al., 2003; Kellet, 2011). For example, the approach to fragmentation processes might fix the attention of planners on attrition, shrinkage, and increased isolation. Although these metrics describe the change, they also include the idea of isolation where remnant habitats are surrounded by a non-habitat matrix (Leitao and Ahern, 2002). This idea denies the changing role of the matrix in a resilient system. Among others, Leitao and Ahern (2002) and Gallent et al. (2006) argue that instead of present containments, we should work with socioecological processes and human activities as integral parts of ecological systems in the urban context.

Moreover, Lindholm (2017) argues that it is difficult to display both ownership and greenery in a printed representation that describes all the shades of urban green spaces. This same difficulty applies to all kinds of representations of multifunctionality. Here, we can add the difficulty of displaying possible paths of change to this representation challenge.

3.3. Domestic private gardens

Private gardens form a heterogeneous urban fabric which represents a substantial element of green space in many urban areas of the world (Gaston et al., 2005b; Mathieu et al., 2007; Gonzáles-García and Gómez Sal, 2008). In the UK, private gardens cover 16% of the urban area (Loram et al., 2007); in New Zealand, 36% (Mathieu et al., 2007); and in Stockholm, 16% (Colding, 2007). This green resource is extensive but difficult to control with conventional planning methods. If urban planning perceives LDH only by density and population, it ignores the potential of complementary urban green areas that are provided and maintained privately.

Scientific interest in private gardens has concentrated on gardens as a part of urban green spaces based on their vegetation and biodiversity potential, as a part of storm water management by the proportion of impermeability and its change, and individual well-being and psychology. Dewaelheyns et al. (2014) state that gardens and gardening have both positive and negative impacts on urban ecology as the context relies mainly on the debate on exotic and native plants in home gardens and the role of lawns in urban ecology. If debate concentrates on positive and negative effects, residents' engagement in promoting the urban green area in general is lost. According to Nassauer et al. (2014), household-scale mechanisms are core elements of natural and human systems studies. However, recent studies on private gardens concentrate either on the social aspects or the ecological aspects (Cook et al., 2011).

The biodiversity potential of private gardens has been mentioned in several recent studies (Young et al., 2009; Taylor Lovell and Taylor, 2013). Goddard et al. (2016) divided garden-scale ecological drivers to garden-scale features and different habitat types that are based on preferences in garden styles. Additionally, Ignatieva et al. (2011) argued the potential importance of this garden matrix as it involves all kinds of potential spaces that provide sources for biodiversity in cities. Furthermore, Beumer and Martens (2014) concluded that cultural landscapes generate considerable ecological values, and much of these exist in private or semi-private domestic gardens.

As Cook et al. (2011) summarized, the 'luxury effect' makes certain neighbourhoods or plots valuable for urban biodiversity because the owners have the financial ability to create multilayered and species-rich plantings. The prestige effect also makes them symbolic displays of identity and social status. Although there are several studies on private gardens, they may still be the least understood ecological habitat type when compared to other types of urban greenspace like Mathieu et al. claimed in 2007.

4. Garden characteristics

The five themes in this categorization are the common denominators found in thematic groups in our review. Anthropocentric garden studies concentrate on a human-oriented approach, viewing a garden as a place and an activity. Studies on garden typologies link zoning and planning to individual plots and the arrangement of a garden with a building. Economic properties are studied as property values based on gardens and as the value of separate elements. Studies on surface coverage concentrate mainly on impermeability and the non-point management of storm water or vegetation coverage. Point-oriented features are studied in wildlife gardening and certain practices in sustainable drainage. Vegetation is studied, if not on surface coverage, then on species richness or structural elements (Fig. 1).

Sociocultural sustainability in residential gardens relies on the garden as a physical site and on the properties that gardening, as an activity, requires. The garden, as a place, provides social sustainability when there is sufficient distance to view the outdoor spaces from inside the building, when one can feel sheltered in the garden, and when there is an area needed for vital vegetation. For gardening to be an activity, there needs to be a connection to the soil (the foundation of gardening)—an area where the soil can retain water and nutrients and receive sufficient daylight for vegetation growth.

As Freeman et al. (2012) claim, gardens provide a physical site used by residents for both passive and active enjoyment. The garden, as a physical place, is studied not only in a concrete way according to

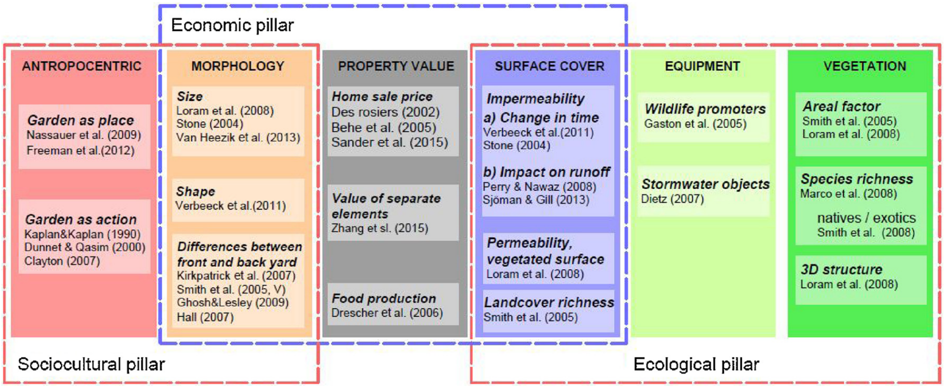

Fig. 1. Studies on private domestic gardens and their role in sociocultural, economic, and ecological sustainability.

tangible benefits such as food production and additional living space but also as an expression of identity and a place to provide a connection to or experience nature. Gardening, as an action, studies gardening and its time use, different activities, and benefits such as physical health, social inclusion, self-esteem, and relaxation (Kaplan and Kaplan, 1990; Dunnett and Qasim, 2000; Clayton, 2007; Nassauer et al., 2009; Freeman et al., 2012). Several studies on nature's restorative and human health benefits have been published, but they do not clearly address the scale of gardens or the LDH environment.

Garden morphology represents the order and form of the physical plot where the buildings define the layout of garden spaces. Residential morphology determines the typology of a single plot and creates a frame in which to organize hard surfaces, vegetation, and the functions provided by these surfaces. At the neighbourhood scale, Zmyslony and Gagnon (1998) presented a mimicry effect that explains the repetition of garden elements at the local scale. Neighbourhood norms affect individual preferences and, therefore, the physical environment.

Economically sustainable solutions concentrate on property values but also look for economic solutions that replace all or some of the solutions provided by the grey infrastructure such as storm water management, noise and pollution reduction, and improvement in the residential microclimate. The basis for economic sustainability is determined when the formal design of LDH is planned and its traffic system and placement in the topography is completed.

Studies on urban garden sizes in the UK show an average size of 190 m^2 (Davies et al., 2009), ranging from 151 to 197 m^2 (Loram et al., 2008). Stone (2004) and Verbeeck et al. (2011) studied residential imperviousness and used lot size rather than garden size to describe residential surface coverage. Stone (2004) found that the mean parcel size in Madison, Wisconsin, USA, is 911 m^2; Verbeeck et al. (2011) found that in five different areas in Belgium, it ranges from 154 to 845 m^2. Comparing garden and even parcel sizes is difficult and produces a wide range of results. Housing density determines garden size (Tratalos et al., 2007), and the size of garden areas (i.e. the vegetated areas) is considered one of the most important determinants of plant and bird diversity (van Heezik et al., 2013; Smith et al., 2005; Loram et al., 2008). A garden area is determined not only by the parcel size but also by the size of the building and its footprint. The average building's roof size in one area might be twice as large in another area (Ghosh and Head, 2009), often occupying one-third of the plot (Hall, 2007). Studies on detached houses report an average of 315 m^2 in the UK (Loram et al., 2008). In an Australian comparison, most garden spaces were 451–500 m^2 or 301–350 m^2, depending on housing density (Ghosh and Head, 2009), and in New Zealand, it was 755 m^2 (van Heezik et al., 2013).

Studies on property values have sought to identify elements that increase a home's sale price. Des Rosiers et al. (2002) found that trees in the plot or the nearby neighbourhood, vegetation, sheltered space, and a deck or sitting area had a positive effect on property values. Behe et al. (2005) argued that a good landscape that was defined by design sophistication, plant sizes, and plant material type increased a home's property value by 5–11%. Recently, Sander and Zhao (2015) found that tree cover has a positive effect on home sale prices. Additionally, views of grassy, agricultural, forested, and wetland landscapes had the same effect in their study, although these qualities mainly depend on the surrounding areas rather than the plot's qualities. Individual elements have also been used to study direct economic value; for example, Zhang et al. (2015) studied the capitalized value of rainwater tanks.

A parcel's surface cover is studied to clarify impermeability (Verbeeck et al., 2011; Stone 2004) and its effects on surface runoff (Perry and Nawaz, 2008) as well as describe the proportion of vegetative surfaces (Loram et al., 2008), residential patch size (Tratalos et al., 2007), and land cover richness (Smith et al., 2005). Regional catchment studies on increasing impermeability and its effects on non-source pollution and flooding requires focusing on parcel scale. As Arnold and Gibbons (1996) claim, a certain percentage of impervious coverage of a watershed affects stream health. Changes in impervious surfaces was studied by Verbeeck et al. (2011) and Perry and Nawaz (2008). They both demonstrate a slow but perceptible increase in impermeable surfaces in residential areas and its outcome as increased urban runoff. Tratalos et al. (2007) claim that individual garden size is a strong indicator of land cover composition.

Ecological sustainability within gardens is based mainly on vital vegetation and its ability to provide a liveable environment for fauna. Soil, water, light, nutrients, and a suitable temperature are required to provide self-supporting vegetation and biodiversity in man-made or semi-natural environments. Biodiversity is based on species richness and the microbiology of soils, which requires space for soil formation and litter decomposition. The cycles of water, nutrients, and organic matter need space to provide self-supporting vegetation.

Garden vegetation is studied as an areal factor (Smith et al., 2005; Loram et al., 2008), variation in species richness (Smith et al., 2006; Loram et al., 2008), and vegetation structure (Smith et al., 2005). Vegetation as an areal factor is measured in various ways, depending on the method used. Tratalos et al. (2007) combine similar areas that are 10 m apart in GIS-based mapping on the scale of residential areas. As an areal factor, vegetation is utilized to represent the contribution of gardens to urban green spaces (Gaston et al., 2005b; Loram et al., 2007) and biodiversity by possible habitat provision (Davies et al., 2009) whereas species richness mainly concentrates on urban biodiversity and more specifically on exotic and native species (Smith et al., 2006). To study the structure of garden vegetation as a three-dimensional composition of vegetation, Loram et al. (2008) mapped vegetation by several heights and explained the relevance of multilayered vegetation to biodiversity.

Equipment as a garden metric are the objects of a garden that are spotlike, retrofittable, and focus mainly on a single function. An especially ecological approach to garden features is mapping equipment for evaluating and improving wildlife gardening. Gaston et al. (2005a) mapped artificial nest sites for bees, wasps, and bumblebees; small ponds; dead trees; and patches of nettles in a study of the extent of wildlife gardening practices in residential areas. Gaston et al. (2005b) continued the mapping process by including ponds, nest boxes, compost heaps, and cats.

A technical approach can also be found in the form of equipment in gardens. Storm water management offers a solution for sustainable urban drainage, and rain barrels, cisterns, and some rain gardens have the characteristic nature of equipment as defined in this review. Sustainable storm water management and its practices are studied as separate components concentrating either on quality or quantity (e.g., Dietz, 2007). In both these examples of garden equipment studies, the garden is regarded as a part of the urban matrix, providing a home and the possibility of wildlife movement or managing storm water in a decentralized manner. After all, many wildlife-friendly features and sustainable storm water management practices on a garden scale are add-ons in nature and, therefore, easy to add and easy to remove. Mapping these features provides information as to their extent on a certain date, but a resident's interest can change quite rapidly.

5. The potential of gardens

The purpose of the previous classification of reviewed studies was to first develop a checklist, and then garden-scale properties are projected to the block scale. The proposed checklist aims to provide backing for practical planning processes that frame the possibilities for gardens.

5.1. Sustainable potential of gardens

All components of sustainable development can be found in studies on private gardens as a scaling-up approach. Ecological sustainability relies first on species richness and defining features promoting ecological functioning and secondly on the variation in surface coverage. Sociocultural sustainability builds on private gardens as places and as actions, but it is also defined by the form of the residential area, which determines the size, shape, and proportion of front and back gardens. Economic sustainability is also based on typology and especially garden size. However, in addition, surface coverage and some garden features define a garden's capacity for storm water management.

We developed the reviewed studies and the categories they form into a checklist (Fig. 2). The checklist outlines the requirements for gardens as a physical environment as it forms the platform for social and economic dimensions as well as cyclic processes of water, nutrients, and carbon. This physical environment, or eco-physical dimension as Termorshuizen et al. (2006) describe it, is a clear outcome of the planning process.

This checklist has several points concerning garden size. This comes from certain functions that require a standard amount of space such as automobile parking or tree growth. A defined space for vegetation should be expressed in square metres rather than percentages or proportions. This is to ensure proper soil volume for the self-sufficient growth of plants. However, there are possible ways to exploit the qualities between the neighbouring plots. The location of buildings, pavement, and vegetation define the outline for views as well as the location of the plot’s sheltered areas, the division between front and back yards, and the shared soil volume across the borders.

Garden size is one of the main factors used to define land use efficiency, and therefore causes urban sprawl via low-density housing. This should not lead to a demand to define the minimum size of gardens that retain the potential for multifunctionality. Although space-dependent functions may not be scaled to insufficient space, multifunctionality can be further enabled on block or district scales.

The elements of sustainability seem to be quite concrete on the plot scale, but as the scale changes, the complexity increases. Fig. 3 summarizes the possibility of managing and implementing concrete solutions by different sustainability pillars on different scales. The district scale combines two or all three pillars of sustainability, but garden-scale sustainability builds up from separate pillars.

5.2. Scaling up to blocks and neighbourhoods

Systems theory uses holistic thinking in which the whole is greater than the sum of its parts. This approach considers individual elements of a system to have several interconnections that may modify the system or produce something new. Complexity, the adaptability of single elements, and interactions among single elements are the power of a system. This power may provide new phenomena in the system’s upper level. The emerging phenomena have properties or qualities that do not exist in the lower level elements and require numerous diverse single elements and multiple connections between elements. However, the number or qualities of the elements do not guarantee emergence (Manson, 2001).

Private domestic gardens and their qualities can be interpreted as lower-level elements in systems theory, enabling private gardens to serve as the core for emerging block or district scales. Specifically, the

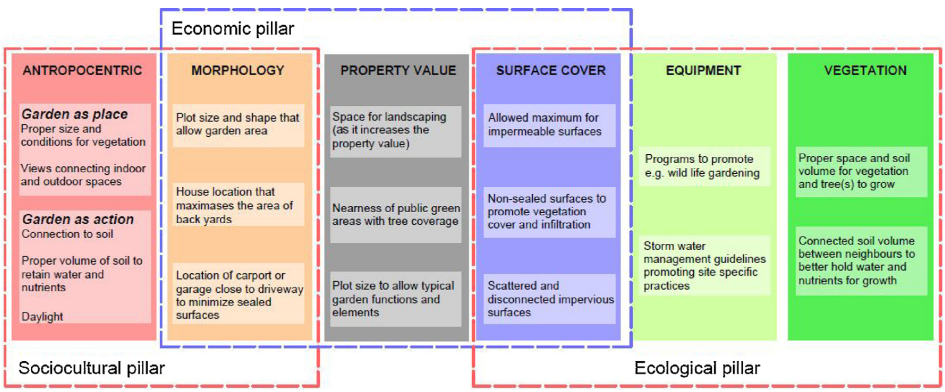

Fig. 2. A checklist proposal for urban planning to enhance the potential of gardens in the physical environment of LDH.

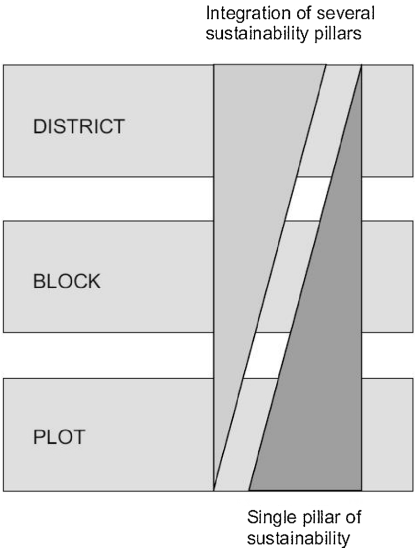

Fig. 3. The integration level of sustainability pillars on different scales. The scaling-up approach implements sustainability by separate pillars on the plot scale. However, this set of simple solutions on the plot scale may provide new sustainable functions on block or even district scales. These functions (provided by the scaling-up approach) support plot-scale sustainability. If sustainability is only recognized as a top-down feature during the planning process, the plot scale may fail to fulfil expectations.

functions and elements that gardens contain on a plot scale provide valuable and irreplaceable power to produce new and unpredictable functions on block or district scales. This power needs to be comprehended and protected to remain adaptable to systems theory. New functions that arise allow planners to rethink plot scale qualities, for example, garden size.

How does this review and its scaling-up approach to gardens help formulate a model for sustainable urban planning? It provides two results. First, the review demonstrates the potential that a single domestic urban garden has for ecological, sociocultural, and economic-technical sustainability. This serves the qualities and quantities of lower-level elements in systems theory. The second result appears as scaling from the plot scale to block or district scales. This scaling may generate the emergence of some new garden-related functions (Fig. 4). For example, plot-scale gardening requires space to pre-grow vegetables and bedding plants, facilities for soil storage and composting, and ownership and storage of machinery. Some of these space-consuming functions may be considered on a block or a district scale, and at the same time it could build a community by joint or shared ownership. Understanding the plot-scale functions and components of sustainability provide possibilities for planners to integrate some plot scale functions on a wider scale. The main motivation is not a single plot or its garden but the united outcome of gardens in blocks or neighbourhoods.

Manson (2001) claims that emergent phenomena may lie beyond our ability to predict or control. For urban planning, it means that all the emergent phenomena from private gardens cannot be planned. Therefore, it is essential that urban planning not only recognizes the potential of private gardens on the plot scale but also reserves space on the block and district scales for emergent needs appearing on the plot scale. More specifically, the management of LDH and its qualities, as scaling up from gardens, is both a strategic question and a policy issue. Planning process only creates biophysical platforms for continuation.

Residential areas often cover large areas, even when compared to the other forms of urban and suburban green space. In Europe, the extent of residential areas is increasing, regardless of population growth or decline (Kabisch and Haase, 2013). This requires urban planning to re-evaluate LDH in the sustainable city paradigm from two perspectives. First, LDH should not be underrated for its potential if there is sufficient space for the processes and functions of ecological, social, and technical sustainability. Secondly, housing density provides possibilities for processes and functions, but a dichotomy between dense and green should not be the result. Discussion on the shades of green or the qualities of urban green areas (as Ståhle, 2010 and Smith et al., 2009 describe it) should ideally lead to more constructive approaches. The GI

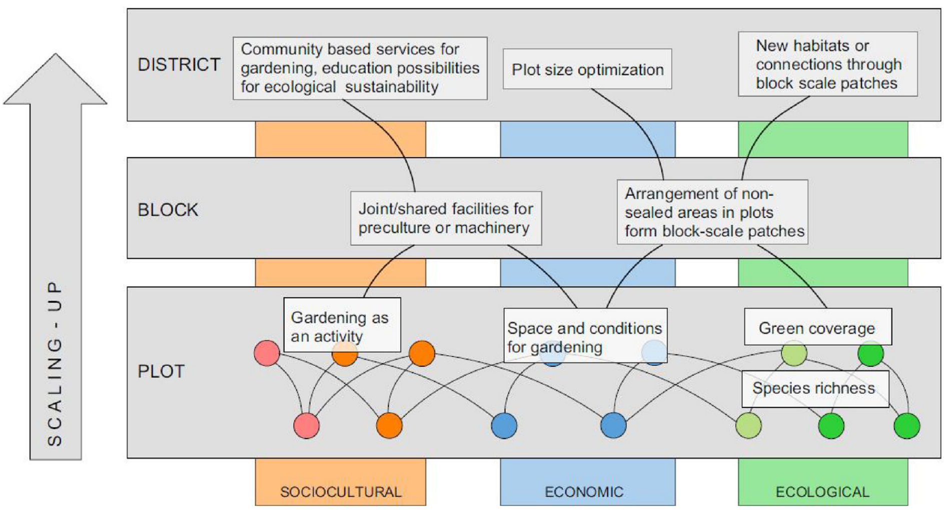

Fig. 4. Plot scale elements, their numerous properties, and their connections provide the potential for higher-level emergent phenomena. Here, different elements follow the pillars of sustainability on the plot scale and provide new possibilities for land-use planning to encourage sustainability. This figure illustrates the possibilities for plot-scale green coverage, gardening, appropriate conditions, and space to influence other scales (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

planning process defines the wise use of resources and allows appropriate functions to support vegetation growth in the planned area.

Because densification is a risk of multifunctional LDH, we proposed a multiscaled approach to retaining garden-based functions. Emergent phenomena from the garden scale may provide convenient garden-based functions on block or even neighbourhood scales that improve social or economic sustainability. Multi-scaled functions, or affordances for emergent phenomena, are a challenge to plan in the zoning phase because they are unpredictable. However, possibilities or the space reserved for block- and neighbourhood-scale emergent phenomena supports the idea of the resilience inherent in GI. This is in line with Mell's (2008) claim that GI is not a quick fix solution but rather a slow process to support development. As Cameron et al., 2012 summarized, planners need to choose whether they prioritize private gardens or invest in communal green spaces. Therefore, LDH could also take a role in urban green area provisioning or follow Colding (2007) idea of ecological land-use complementation in planning practices.

6. Conclusion

This literature-based study identified the spectrum of functions that take place in private domestic gardens and yards. There appears to be a wide range of topics related to gardens' ecological, economic, and sociocultural functions. If this scene of multifunctionality is considered through the lens of green infrastructure, its basis lies on a biophysical platform that provides vegetation growth and requires space for growth-supporting processes. These natural and vegetative cyclic processes will utilize space that is not resized or determined based on densification demands. Planners need to know the processes to allocate sufficient space for them. However, this platform is not only an ecological feature in urban planning but also a seedbed for economic and sociocultural functions. For example, the cultural value of a garden is not provided without water, light, and a certain temperature. In addition to the space requirement for cyclic processes, planners need to allocate space enabling multifunctionality in garden scale. Multiple functions in garden scale can be considered as lower level elements in systems theory, and this potential may provide emergencies to upper levels. Possibility for emergencies, in turn, support the resilience of the entire LDH.

LDH provides unique and constantly changing ecological matrix for cities. This novel ecosystem is difficult to manage, builds on inefficient land use, may cause disservices but it has also an interesting potential in the context of resilience in sustainable cities. Garden scale multifunctionality provides obviously ongoing changes for the characteristics of LDH as a whole, but simultaneously it is a resource to link different scales, and build up for resiliency for its part in sustainable cities.

Acknowledgements

Thanks to professor Raine Mäntysalo for consistent support in the writing process. This research received funding from the Rikala Foundation.

References

Ahern, J., 2013. Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design. Landsc. Ecol. 28, 1203–1212.
Ahern, J., 2011. From fail-safe to safe-to-fail: sustainability and resilience in the new urban world. Landsc. Urban Plan. 100, 341–343.
Ahern, J., Cilliers, S., Niemelä, J., 2014. The concept of ecosystem services in adaptive urban planning and design: a framework for supporting innovation. Landsc. Urban Plan. 125, 254–259.
Arnberger, A., 2012. Urban densification and recreational quality of public urban green spaces – a Viennese case study. Sustainability 4, 703–720.
Arnold, C., Gibbons, J., 1996. Impervious surface coverage. The emergence of a key environmental indicator. J. Am. Plann. Assoc. 62, 243–258.
Behe, B., Hardy, J., Barton, S., Brooker, J., Fernandez, T., Hall, C., Hicks, J., Hinson, R., Knight, P., McNiel, R., Page, T., Rowe, B., Safley, C., Schutzki, R., 2005. Landscape plant material size, and design sophistication increase perceived home value. J. Environ. Hortic. 23, 127–133.
Blicharska, M., Smithers, R., Hedbom, M., Hedenås, H., Mikusinski, G., Pedersen, E., Sandström, P., Svensson, J., 2017. Shades of gray challenge practical application of the cultural ecosystem services concept. Ecosyst. Serv. 23, 55–70.
Beumer, C., Martens, P., 2014. Biodiversity in my (back)yard: towards a framework for citizen engagement in exploring biodiversity and ecosystem service in residential gardens. Sustain. Sci. 10, 87–100.
Byrne, L., 2007. Habitat structure: a fundamental concept and framework for urban soil ecology. Urban Ecosyst. 10, 255–274.
Cameron, R., Blanusa, T., Taylor, J., Salisbury, A., Halstead, A., Henricot, B., Thompson, K., 2012. The domestic garden – its contribution to urban green infrastructure. Urban For. Urban Green. 11, 129–137.
Campbell, S., 1996. Green cities, growing cities, just cities? Urban planning and the contradictions of sustainable development. J. Am. Plan. Assoc. 62, 296–312.
Clayton, S., 2007. Domesticated nature: motivations for gardening and perceptions of environmental impact. J. Environ. Psychol. 27, 215–224.
Colding, J., 2007. 'Ecological land-use complementation' for building resilience in urban ecosystems. Landsc. Urban Plan. 81, 46–55.
Cook, E., Hall, S., Larson, K., 2011. Residential landscapes as social-ecological systems: a synthesis of multi-scalar interactions between people and their home environment. Urban Ecosyst. 15, 19–52.
Davies, Z.G., Fuller, R.A., Loram, A., Irvine, K.N., Sims, V., Gaston, K.J., 2009. A national scale inventory of resource provision for biodiversity within domestic gardens. Biol. Conserv. 142, 761–771.
Des Rosiers, F., Thériault, M., Kestens, Y., Villeneuve, P., 2002. Landscaping and house values: an empirical investigation. J. Real Estate Res. 23, 139–161.
Dewaelheyns, V., Rogge, E., Gulinck, H., 2014. Putting domestic gardens on the agenda using empirical spatial data: the case of Flanders. Appl. Geogr. 50, 132–143.
Dietz, M.E., 2007. Low impact development practices: a review of current research and recommendations for future directions. Water Air Soil Pollut. 186, 351–363.
Dunnett, N., Qasim, M., 2000. Perceived benefits to human well-being of urban gardens. HortTechnology 10, 40–45.
Forman, R., 1995. Land Mosaics: the Ecology of Landscapes and Regions. Cambridge, Cambridge.
Forman, R., Godron, M., 1986. Landscape Ecology. Wiley, New York.
Francis, R., Chadwick, M., 2013. Urban Ecosystems: Understanding the Human Environment. Routledge, London.
Freeman, C., Dickinson, K.J.M., Porter, S., van Heezik, Y., 2012. "My garden is an expression of me": exploring householders' relationship with their gardens. J. Environ. Psychol. 32, 135–143.
Gallent, N., Andersson, J., Bianconi, M., 2006. Planning on the Edge: The Context for Planning at the Rural-urban Fringe. Routledge, London.
Gaston, K.J., Smith, R.M., Thompson, K., Warren, P.H., 2005a. Urban domestic gardens (II): experimental tests of methods for increasing biodiversity. Biodivers. Conserv. 14, 395–413.
Gaston, K.J., Warren, P.H., Thompson, K., Smith, R.M., 2005b. Urban domestic gardens (IV): the extent of the resource and its associated features. Biodivers. Conserv. 14, 3327–3349.
Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., 2007. Adapting cities for climate change: the role of the green infrastructure. Built Environ. 33, 115–133.
Ghosh, S., Head, L., 2009. Retrofitting the suburban garden: morphologies and some elements of sustainability potential of two Australian residential suburbs compared. Aust. Geogr. 40, 319–346.
Goddard, M.A., Dougill, A.J., Benton, T.G., 2010. Scaling up from gardens: biodiversity conservation in urban environments. Trends Ecol. Evol. 25, 90–98.
Goddard, M.A., Ikin, K., Lerman, S.B., 2016. Ecological and social factors determining the diversity of birds in residential yards and gardens. In: Murgui, E., Hedblom, M. (Eds.), Ecology and Conservation of Birds in Urban Environments. Springer, Heidelberg.
Gonzáles-García, A., Gómez Sal, A., 2008. Private Urban greenspaces or "Patios" as a key element in the urban ecology of tropical central America. Hum. Ecol. 36, 291–300.
Grimm, N., Faeth, S., Golubiewski, N., Redmaan, C., Wu, J., Bai, X., Briggs, J., 2008. Global change and the ecology of cities. Science 319, 756–760.
Hall, T., 2007. Where have all the Gardens Gone? An Investigation into the Disappearance of Yards in the Newer Australian Suburb. Urban Research Program, research paper 13.
Ignatieva, M., Stewart, G., Meurk, C., 2011. Planning and design of ecological networks in urban areas. Landsc. Ecol. Eng. 7, 17–25.
Kabisch, N., Haase, D., 2013. Green spaces of European cities revisited for 1990-2006. Landsc. Urban Plan. 110, 113–122.
Kaplan, R., Kaplan, S., 1990. Restorative experience: the healing power of nearby nature. In: Francis, M., Hester, R.T. (Eds.), The Meaning of Gardens. MIT Press, Cambridge.
Kellet, J., 2011. The Australian quarter acre block: the death of a dream? Town Plan. Rev. 82, 263–284.
Leitao, A., Ahern, J., 2002. Applying landscape ecological concepts and metrics in sustainable landscape planning. Landsc. Urban Plan. 59, 65–93.
Loram, A., Warren, P.H., Gaston, K.J., 2008. Urban domestic gardens (XIV): the characteristics of gardens in five cities. Environ. Manage. 42, 361–376.
Loram, A., Tratalos, J., Warren, P.H., Gaston, K.J., 2007. Urban domestic gardens (X): the extent & structure of the resource in five major cities. Landsc. Ecol. 22, 601–615.
Lindholm, G., 2017. The implementation of green infrastructure: relating a general concept to context and site. Sustainability 9, 610.
Manson, S., 2001. Simplifying complexity: a review of complexity theory. Geoforum. 32, 405–414.
Mathieu, R., Freeman, C., Aryal, J., 2007. Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery. Landsc. Urban

Plan. 81, 179–192.
Matlock, M., Morgan, R., 2011. Ecological Engineering Design. Restoring and Conserving Ecosystem Services. Wiley, NJ.
Marris, E., 2011. Rambunctious Garden, Saving Nature in a Post-Wild World. Bloomsbury, New York.
McGarigal, K., Cushman, S.A., 2002. Comparative evaluation of experimental approaches to the study of habitat fragmentation effects. Ecol. Appl. 12, 335–345.
Mell, I., 2008. Can green infrastructure promote urban sustainability? Eng. Sustainability 162, 23–34.
Nassauer, J.I., Cooper, A., Marshall, L., Currie, W., Hutchins, M., Brown, D., 2014. Parcel size related to household behaviors affecting carbon storage in exurban residential landscapes. Landsc. Urban Plan. 129, 55–64.
Nassauer, J.I., Wang, Z., Dayrell, E., 2009. What will the neighbors think? Cultural norms and ecological design. Landsc. Urban Plan. 92, 282–292.
Naveh, Z., 1995. Interactions of landscapes and cultures. Landsc. Urban Plan. 32, 43–54.
Penteado, H., 2013. Assessing the effects of applying landscape ecological spatial concepts on future habitat quantity and quality in an urbanizing landscape. Landsc. Ecol. 28, 1909–1921.
Perry, T., Nawaz, R., 2008. An investigation into the extent and impacts of hard surfacing of domestic gardens in an area of Leeds, United Kingdom. Landsc. Urban Plan. 86 (1), 13.
Sander, H., Zhao, C., 2015. Urban green and value: who values what and where? Land. Use Policy 42, 194–209.
Sijtsma, F., de Vries, S., van Hinsberg, A., Diederiks, J., 2012. Does 'grey' urban living lead to more 'green' holiday nights? A Netherlands case study. Landsc. Urban Plan. 105, 250–257.
Smith, R., Gaston, K., Warren, P., Thompson, K., 2005. Urban domestic gardens (V): relationships between land cover composition, housing and landscape. Lands. Ecol. 20, 235–253.
Smith, C., Clayden, A., Dunnet, N., 2009. An exploration of the effect of housing unit density on aspects of residential landscape sustainability in England. J. Urban Des. 14, 163–187.
Smith, R.M., Thompson, K., Hodgson, J.G., Warren, P.H., Gaston, K.J., 2006. Urban domestic gardens (IX): composition and richness of the vascular plant flora, and implications for native biodiversity. Biol. Conserv. 129, 312–322.
Stone, B., 2004. Paving over paradise: how land use regulations promote residential imperviousness. Landsc. Urban Plan. 69, 101–113.
Strandell, A., Hall, M.C., 2015. Impact of the residential environments on second home use in Finland – testing the compensation hypothesis. Landsc. Urban Plan. 133, 12–23.
Ståhle, A., 2010. More green space in a denser city: critical relations between user experience and urban form. Urban Des. Int. 15, 47–67.
Taylor Lovell, S., Taylor, J.R., 2013. Supplying urban ecosystem services through multifunctional green infrastructure in United States. Landsc. Ecol. 28, 1447–1463.
Termorshuizen, J., Opdam, P., van den Brink, A., 2006. Incorporating ecological sustainability into landscape planning. Landsc. Urban Plan. 79, 374–384.
Thompson, K., Austin, K., Smith, R., Warren, P., Angold, P., Gaston, K., 2003. Urban domestic gardens (I): putting small-scale plant diversity in context. J. Veg. Sci. 14, 71–78.
Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G., Gaston, K.J., 2007. Urban form, biodiversity potential and ecosystem services. Landsc. Urban Plan. 83, 308–317.
Uggla, Y., 2012. Construction of 'nature' in urban planning: a case study of Stockholm. Town Plan. Rev. 83, 69–85.
United Nations, 2015. World Urbanization Prospects. The 2014 Revision. Department of Economic and Social Affairs, New York accessed 20.5.2017. https://esa.un.org/unpd/wup/publications/files/wup2014-Report.pdf.
Van Heezik, Y., Freeman, C., Porter, S., Dickinson, K.J.M., 2013. Garden size, householder knowledge, and socio-economic status influence plant and bird diversity at the scale of individual gardens. Ecosystems 16, 1442–1454.
Verbeeck, K., Van Orshoven, J., Hermy, M., 2011. Measuring extent, location and change of imperviousness in urban domestic gardens in collective housing projects. Landsc. Urban Plan. 100, 57–66.
Werner, P., 2011. The ecology of urban areas and their function for species diversity. Landsc. Ecol. Eng. 7, 231–240.
Wu, J., 2013. Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landsc. Ecol. 28, 999–1023.
Young, C., Jarvis, P., Hooper, I., Treuman, I., 2009. Urban landscape ecology and its evaluation: a review. In: DuPont, A., Jacobs, H. (Eds.), Landscape Ecology Research Trends. Nova Science Publishers, New York.
Zhang, F., Polyakov, M., Fogarty, J., Pannel, D., 2015. The capitalized value of rainwater tanks in the property market of Perth, Australia. J. Hydrol. 522, 317–325.
Zmyslony, J., Gagnon, D., 1998. Residential management of urban front-yard landscape: a random process? Landsc. Urban Plan. 40, 295–307.

Paper 2

II

Tahvonen, Outi. 2018. Impervious Coverage in Finnish Single-Family House Plots. Potential of low-density residential areas in stormwater management and creating urban green spaces. Architectural Research in Finland, 2, 180-194.

Impervious Coverage in Finnish Single-Family House Plots

Potential of low-density residential areas in stormwater management and creating urban green spaces

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Abstract
Single-family house areas account for a significant percentage of the total square area of cities. Where statutory land use planning is concerned, single-family house areas and single-family house plots in Finland are usually addressed only in terms of housing, even though the impervious surfaces their construction creates also determine the cause of stormwater runoff and urban green spaces.

This study will explore the specification of impervious surfaces in the single-family plots of modern-day Finland. Impervious surfaces are a key factor in causing stormwater runoff and the deterioration in the condition of catchment area streams. At the same time, impervious surfaces seal the ground surface and prevent vegetation from growing at each site. The research subject involved three plots in a housing fair area and their garden plan (N = 63), which represent sites completed in the same area. Housing fairs present individual consumers with the ideal of single-family housing as proposed by commercial developers.

Permeable and impervious surfaces and their detailed breakdown into different surface types were measured in the plans. Although a considerable percentage of the impervious surface area in a modern-day Finnish plot is formed by garden surfaces, vehicle parking and various types of shelters and roofs also play a role in the formation of imperviousness. Used as a tool in statutory land use planning, plot density does not specify plot permeability, in which the roof square area is the primary factor. When defining the area of imperviousness, statutory land use planning could make use of the maximum allowable roof square area and/or the maximum allowable amount of impervious surface coverage as well as reduce the need for surfaced passageways by placing the parking space and residential building centrally within the plot. Setting guidelines for the amount of green space within a plot is more challenging, because the changing needs of residents significantly influence plot landscaping.

Keywords: low-density housing, housing density, garden size, imperviousness, plot scale, Housing Fair Finland

Introduction
Urbanisation will remain a global phenomenon as population growth accelerates and the economic structure undergoes change. The expansion of cities consumes more and more land area, including arable land, thus eating into the food production capacity for urban residents. The two extremes of urban growth

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strategies are a decentralisation of the urban structure or a consolidation of the existing urban structure. Decentralisation of the urban structure results in the need for a more extensive infrastructure in the form of transportation systems, water and wastewater networks, and power and data transmission channels. Consolidation of the urban structure is based on the principles of sustainable development and, in particular, environmental sustainability, so that growth of the land area covered by the city remains moderate. Despite urban growth strategies, urbanisation and urban growth inevitably mean an increase in the amount of water-impervious surfaces. A city creates impervious surfaces.

An impervious surface is any surface, regardless of the material, that prevents water from being absorbed into the ground. Schuler (1994, 100) defines impervious surfaces in urban areas as: "[...] the sum of roads, parking lots, sidewalks, rooftops, and other impermeable surfaces of the urban landscape." Schuler (1994, 100) further refines his definition by stating that: "This variable can be easily measured at all scales of development, as the percentage of area that is not 'green'." Stone (2004, 102) states that the rapid growth of impervious surfaces poses the greatest threat to the condition of urban streams. Imperviousness refers to all surfaces through which water cannot pass, such as asphalt and stone paving on roads and parking lots as well as different types of roofs and shelters.

Impervious surfaces

Both Arnold and Gibbons (1996) and Schuler (1994) have highlighted the importance of impervious surfaces to catchment area streams. They emphasise a receiving watershed's capacity to both 1) handle changes in the quantity and quality of water resulting from an increase in impervious surfaces and 2) the ability to recover from changing loads. In their opinion, imperviousness is a precisely measurable and physical indicator, which can be used to unite representatives from all the different fields who are working with urban streams. This makes it possible for architects, city planners, researchers and public officials to work on a scale that encompasses the entire catchment area, even if their own individual job description is but an individual part of the whole.

Imperviousness has a major impact on the receiving watershed. It affects the hydrology, habitat structure, water quality and biodiversity of the water ecosystems. The degradation of watercourses and streams occurs when the 10% of the catchment area is impervious. (Schuler 1994; Arnold & Gibbons 1996; Schuler, Fraley-McNeal & Cappiella 2009).

A locally impervious surface alters the circulation of water, particularly where absorption and surface drainage are concerned. Figure 1 shows the relationship between water absorption and surface drainage when the amount of impervious surface increases.

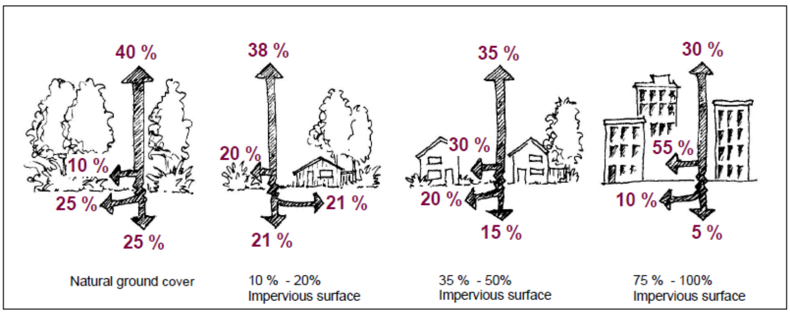

Figure 1. Change in evaporation, surface runoff, surface layer runoff and groundwater outflow with an increase in impervious surface coverage (based on EPA 1993).

An impervious surface does not only act as a physical barrier to water absorption, it also functions as an additional drainage route for the resulting surface runoff. The water flushes pollutants away from impervious surfaces as it flows past. Previously, the guidance and planning of surface water was indeed based on managing water volume and directing water into closed drain and pipe systems, both during flooding caused by heavy precipitation and in order to prevent the erosion of receiving watercourses. Stormwater management imitating natural hydrology, on the other hand, imitates the various processes of water circulation that normally occur in nature.

Increases in impervious surface can also be seen as a broader phenomenon of the challenges facing stormwater management. Roof square areas and paving with stone and asphalt represent a polarised response to a vegetated environment - to urban vegetation. An impervious surface blocks soil nutrients, water reserves and microbial activity--the drivers of vegetative processes--from receiving any sunlight. From an urban ecology standpoint, impervious surfaces therefore limit the possibility for a vegetated environment to exist, ultimately reducing the percentage of urban green space within the total square area.

The building of structures and other impervious surfaces is based on the replacement of substrate mass, in which frost-susceptible soil is replaced with non-frost-susceptible mineral aggregates. According to current recommendations, a substrate mass minimum of 30 centimetres and maximum of over 1 metre must be replaced under asphalt or stone paving. In addition to this, frost protection is augmented with subsurface drainage, i.e. water stored in the ground is channelled away and anti-frost insulation panels are installed. These construction and frost protection methods channel the water required for a vegetated environment even farther away. Although, seams in concrete offer a new type of habitat for plants which thrive in dry environments, thus increasing the range of urban habitats and urban biodiversity within its own scale.

Impervious surfaces in land use planning

Statutory land use planning basically involves the arrangement of different functions within a plan area. Housing, transportation, workplaces and industrial sites as well as well recreational areas can be placed either separate from one another or mixed together. Commonly used plan notations and standardised planning practices do not generally support the placement of several functions within the same area. For example, conventional urban green space planning is used (and is also often considered as having been implemented) in parks, recreational areas and protective green zones, even though urban green spaces are also comprised of gardens in single-family house areas, street tree plantings in traffic zones and the plantings of industrial plots. The processing, requirement and presentation of multifunctionality have not yet been established in statutory land use planning. In the future, an effective statutory land use plan will no longer mean the production of usable floor area, but rather the placement of multiple functions within a single area.

Forming imperviousness and methods for its control

In Finland, the plot-specific formation of impervious surfaces is specified in the (local) detailed plan, architectural and landscaping plan and the constantly changing choices made by residents/users over time. The control system for land use is based on different plans, in which the local detailed plan determines the housing density and general placement of the building(s) on the plot. The local detailed plan implements the guidelines of the local master plan and specifies, in particular, the creation of the cityscape, urban space and functionalities. As a rule, we do not limit the amount of impervious surface coverage formed by the local detailed plan, but have instead recently specified general measures for the measurement of stormwater structures, such as the required retention volumes per impervious surface or guidelines on stormwater treatment methods.

In plot-specific planning, the drafter of a site plan must specify the precise position of the structure (and its distance from the street) as well as the location of parking. These designated vehicle traffic areas are often made as impervious surfaces in order to facilitate their maintenance, positioning a structure far from the street line increases the area of impervious surface coverage. In addition to this, the local detailed plan specifies different types of shelters, roofs and canopies, which increase the percentage of impervious surface coverage within the total square area.

During the landscape planning phase, a motif for the garden area is created, functions are placed and surface materials are specified. Outbuildings, such as storage sheds and playhouses, the extent of lounging areas and surface materials for passageways further increase the percentage of impervious surface coverage. Very small details might have a major impact on resulting surface runoff. For example, curbstones, which are used to direct surface water, collect all the water on the covered area, generally channelling it into a rainwater well. On the other hand, a solution without curbstones might be used to direct water over a broad area for use in vegetation areas, where the resulting stormwater load is absorbed within the plot.

Changes in the amount of impervious surface area also continue after the construction phase. In their study, Verbeeck, van Orshoven and Hermy (2011) found that impervious surface coverage in single-family house areas increased an average of 1.3 m^2 a year in the Flanders region of Belgium. Likewise, Perry and Nawaz (2008) found that impervious surface area in single-family house areas in the United Kingdom had increased 13% from 1971 to 2004. This change occurred gradually in small alterations and remodelling work done in accordance with usage needs and requirements.

The opposite of impervious surfaces, i.e. pervious surfaces, allows for water absorption, water storage in the soil and plant growth, provided that all the habitat factors are in place. Coverage of the ground surface with impervious surfaces prevents the natural circulation of water, shutting down vegetative processes. In a built environment, various habitats are formed in varying conditions.

Impervious surfaces are not the only indicator determining or guiding stormwater management - there are also several concepts related to the management of stormwater and management concepts. The main idea behind all of these is to avoid channelling stormwater directly into the sewer system, place an emphasis on managing both quantity and quality, and give consideration to the use of stormwater in creating a pleasant environment. The aim of American Low Impact Development (LID), European Sustainable Urban Drainage System (SUDS) and Australian Water Sensitive Urban Design (WSUD) is the decentralised and multifunctional management of stormwater (Novotny, Ahern and Brown, 2010). These concepts focus on solutions for the management of existing stormwater, while imperviousness as an indicator seeks to prevent causing stormwater runoff. If the percentage of impervious surface coverage remains low, there will be no stormwater. Impervious surfaces, however, are an integral part of the urban environment, so near-natural stormwater management methods can be employed to reduce the adverse impacts of stormwater coming from impervious surfaces, both in terms of quantity and quality.

Managing the amount of impervious coverage at the catchment area, city and individual plot levels requires different approaches. Arnold and Gibbons (2006, 243), however, state that impervious coverage itself is an indicator that can be used at different levels, something which is clearly understood by all professions involved in urban development. The near-natural management of stormwater is used in an effort to treat already existing stormwater, while impervious surfaces determine how stormwater runoff is caused.

Single-family house areas and plots
Urbanisation requires either new areas or the densification of existing areas in order to provide housing for an increasing population. A compact, densely-built residential area can house a larger number of people than a low-density single-family house area, even though Finnish housing preferences, in particular, clearly favour the latter. Low-density single-family house areas are, however, important in terms of their extent. In the United Kingdom, single-family house areas and their gardens cover 16% of the total urban area (Loram, Tratalos, Warren & Gaston 2007), 36% in New Zealand (Mathieu, Freeman & Aryal 2007) and 16% in Stockholm (Colding 2007).

Single-family house areas offer a platform for both creating urban green space at the private level and the ability to treat stormwater locally. Stone (2004, 102) states that: "...modest changes to municipal land development regulations could yield significant reductions in the total impervious cover of new and existing development." However, the choices made for garden areas in privately-owned single-family house plots are difficult to regulate, as homeowners represent a wide-ranging group, whose plot usage preferences are formed by a myriad of ideas, opinions and ever-changing trends in housing, decor and garden care.

Finnish planning practices do not make use of the multifunctional nature of single-family house areas, with approaches used in urban ecology leaving single-family house areas as blank spaces between parks and urban forests (Vierikko, Salminen, Niemelä, Jalkanen & Tamminen 2014, 39).

The goal of this study is to determine the formation of impervious coverage in single-family house plots as well as the extent of plot vegetation in modern-day Finnish development. The impetus is to examine the potential of single-family house areas in both the local management of stormwater and the creation of urban green spaces at the private level. The research questions are: a) What parts of a modern-day Finnish single-family house plot are covered by impervious surfaces? What indicators can be used in statutory land use planning to regulate the formation of impervious coverage? In addition to the above questions, a question regarding the vegetated environment is: b) What parts of a modern-day Finnish single-family house plot constitute a vegetated environment?

Materials and methods

Site selection
In Finland, Housing Fair Finland is a consumer presentation concept for single-family housing, construction and remodelling. The idea behind housing fairs is to improve the quality of housing in co-operation with companies and organisations at a fair event, which is held in different cities each year. Research data and its application also play a role at housing fairs by: ”[…] [producing] practical applications that provide innovative examples and concrete visions of excellence in living/housing standards, for both consumers and professionals within the industry.” Housing fairs also involve research and development, placing an emphasis on different single-family house planning trials as well as individual test house or test construction research. (Housing Fair Finland 2016).

Each year, housing fairs are attended by approximately 110,000 visitors. According to visitor surveys, these visitors attend year after year in search of information and ideas on not only interior decor, but also gardens and package houses (Housing Fair Finland 2012; Housing Fair Finland 2013; Housing Fair Finland 2014). Housing fairs could therefore be considered a major Finnish event, showcasing the best that Finnish single-family housing has to offer. The event reaches fair visitors directly as well as interested consumers through the media.

The fair gardens shown at the housing fairs in Tampere (2012), Hyvinkää (2013) and Jyväskylä (2014) were chosen as the single-family house sites for this study. The fair sites represent a new vision for good building practices, with the sites using commercially available products and materials. The single-family house sites were primarily designed by industry professionals and statutory land use planning work was done in co-operation with local community hosts. Consequently, the professionals' vision for the fair themes can be seen in the end result. Because statutory land use planning, house construction and landscaping were all done at the same time, the prevailing practices of that time are apparent in the fair sites chosen for this study. Housing fair sites differ from conventional house construction in that impervious surface materials are used in the garden to a greater extent.

The theme at the Tampere, Hyvinkää and Jyväskylä housing fairs included stormwater management in some form. All the fairs showcased the theme of the stormwater management chain across ownership boundaries as a theme. In Hyvinkää, the emphasis was on a stormwater feature placed in a park area, while the fairs in Tampere and Jyväskylä showcased stormwater retention and channelling routes shared by multiple plots and placed in the middle of a residential block. Solutions for the management of already existing stormwater are not a key element of this study, whose primary focus is actually the amount of impervious coverage and the mechanics of its formation. As a result, the stormwater management solutions presented at the fairs will not be discussed in this study. The primary focus is on impervious surfaces, as they cause stormwater runoff by preventing water absorption.

Imperviousness studies often use remote sensing or aerial photography, thus limiting the available data to finished gardens and gardens altered by residents as well as their material choices. In this study, however, the primary focus is on the plans of landscaping professionals and the entity that these plans form.

Collecting data

The data used for this study pertains to single-family house sites at three different housing fairs (a total of 63 sites) and the landscaping plans presented in their fair directories. The plans were scanned and adapted to the scale used in the statutory land use plan, and the different covers were measured using a CAD-based software. Square area measurements were first divided into two main categories: pervious and impervious surfaces. The study examines both plot-specific imperviousness and the perviousness of the garden formed outside the building (Figure 2). Because a garden is defined as the area between the exterior walls of buildings and the plot boundary, it may also comprise covered elements. This definition was created to preserve the functional entities of the garden.

The following measurements were taken in each plot: the square area of plot buildings and their roof square area; impervious surfaces in the garden (stone/tile paving, outbuildings and wood surfaces); and pervious surfaces (aggregate ground covers, preserved areas, lawns and planting areas). The roof square area was measured along the outer edge of the eaves on a carport/garage and (if any) connected shed. In this context, the building square area comprehends the area of both the main building and carport/garage and connected shed measured along the outer edge of the walls. As the shed and carport/garage are integral elements of the architectural plan, often connected to the main building with various types of permanent shelters/roofs, they are included in the total building square area in this study. They also show the impervious coverage specified in the architectural plan as a percentage of the total plot area.

The division into pervious and impervious coverage is not simple, as, for example, wood surfaces might be either pervious or impervious depending on the foundation type. Intended for a large audience, the presentation material does not include detailed information on whether wood surfaces have a cast concrete or crushed aggregate foundation. In this study, all wood surfaces are classified as impervious surfaces.

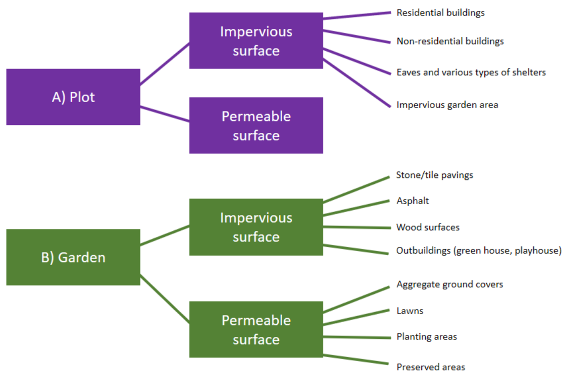

Figure 2. Pervious and impervious coverage are divided into categories, according to which plot-specific measurements are taken in this study.

When examining the plot as a whole, impervious surfaces are divided into the following categories: residential buildings; non-residential buildings; eaves and various types of shelters; and impervious garden surfaces (Figure 3). The residential building category includes residential space used for living functions and is measured based on the floorplan presented in the fair directory, unless otherwise specified in the landscaping plan. The non-residential building category includes non-residential spaces, which were, for example, (out)buildings/sheds, garages and carports (RT-kortti Rakennuksen pinta-alat 2011). However, small garden structures, such as greenhouses or playhouses, were not included in this category. What different spaces are called is not the main focus when dealing with impervious surfaces in plot-specific construction. The main focus is the total roof square area formed. Consequently, the last impervious surface area category related to buildings includes eaves, shelters and various types of canopies and roofs. Depending on its use, the space below a shelter can be either considered a structure (e.g. a greenhouse) or cover part of the lounging area of the garden. A shelter might be an eave that protects the building facade from precipitation or, in terms of amenities, a transparent polycarbonate shelter for a hot tub. In any case, it constitutes part of the garden's impervious coverage.

Figure 3. Formation of impervious coverage in measuring data.

The four categories were used in the measurement of garden imperviousness and perviousness. In the fair gardens, as in any other densely-built single-family house area, the building of pervious surfaces is based on the rebuilding of the substrate as well as seeding it for a lawn or planting vegetation. Existing vegetation is also preserved. Lawns, planting areas regardless of the substrate depth, areas to be preserved and areas to be covered with different types of mineral aggregates were measured as pervious surfaces. Mineral aggregates include cobblestone foundation skirts, dry creeks, stone dust surfaces or artificial grass sand infill. Mineral aggregate surfaces can be partially bound and, as a result, partially impervious, but here they are classified as pervious surfaces.

The impervious garden surfaces category classified paving stones and tiles, asphalt, wood surfaces and outbuilding roof surfaces. In Finnish building practices, paving stones and tiles are often laid on crushed aggregate beds. Depending on the type of stones used, their joints are or can be made to allow for water absorption into the base structural layers, but in this measurement all paving stones and tiles were laid on impervious surfaces. The paving joints do, however, provide a habitat for dry areas and varieties that can withstand trampling Wood surfaces on decks, patios and garden stairs can be founded on a crushed aggregate bed or concrete tiles.

Results and their discussion

Plot-specific impervious coverage in a single-family housing area
The data shows a positive correlation between the planned plot density (e_t) and the impervious coverage of the plot (Figure 4), as one might assume. Generally used as a measuring tool in statutory land use planning, plot density is not a directly applicable indicator for analysing impervious coverage, because, on its own, it does not indicate how many floors are to be placed in the permitted building volume. Even though the scatter diagram in Figure 4 shows a correlation between plot density and impervious coverage, there is also a significant deviation in different plots within the same plot density. For example, the data shows that the impervious coverage within a plot density of 0.35 ranges between 40% and 75% in individual plots.

Where a building is concerned, the roof square area is a key factor in determining the impervious coverage of a plot. When the permitted building volume describes the amount of space for residential use, the roof square area is the real determiner of impervious coverage. Scatter diagram 5 shows the relationship between the building's roof square area and plot density found in the data of this study; there is no statistically significant correlation between these indicators. If the impervious coverage of a single-family house area is to be taken into consideration in statutory land use planning, plot density cannot be used as an indicator for regulating impervious coverage.

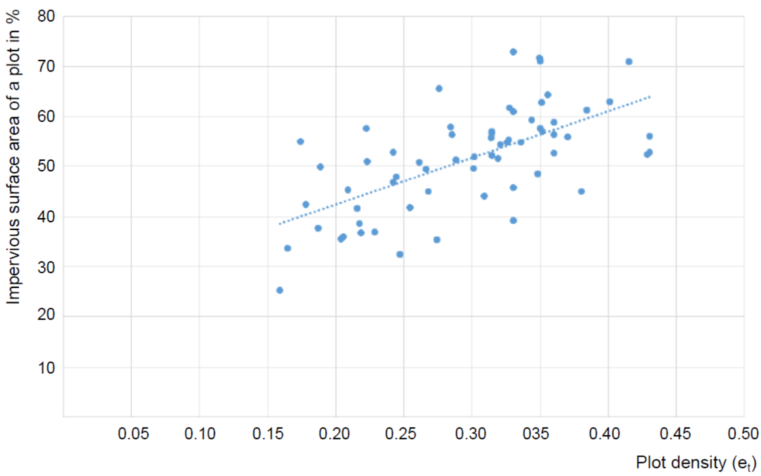

Figure 4. There is a positive correlation between plot density and the impervious surface area of a plot (r = 0.6; 1-way test p-value < 0.001).

Particularly in housing fair sites, the roof square area seems to include a large amount of covered outdoor space, such as in lounging areas, but it also comprehends area covered by various passageways and balconies. This concealed coverage in the permitted building volume quickly and imperceptibly increases the impervious coverage of the plot.

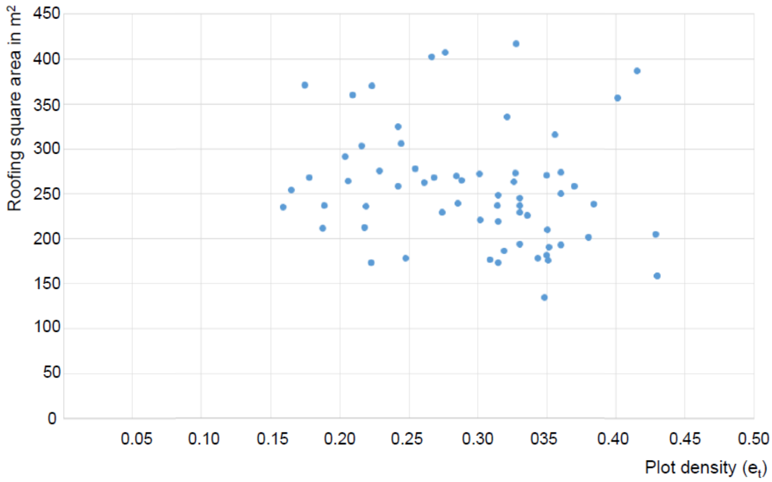

Figure 5. There is no significant correlation between the plot density and roofing square area ($r = -0.24$; 2-way test p-value > 0.05).

A more detailed analysis of roof square area specification in building plans is presented in Figures 6a and 6b. Figure 6a presents the ratio between residential building area and impervious coverage in different plot densities. In this study, the difference between residential building area and impervious coverage stays the same in all plot density classes within the same order of magnitude. In plot density class 0.3-0.39, one can see a decrease in the residential building area compared to other plot density classes, which indicates the more frequent use of multi-storey solutions when moving from plot density class 0.2-0.29 to 0.3-0.39. The interesting thing about the impervious coverage is the difference between the roof square area and residential building area, which averages over 100 m^2 in all plot density classes. This area includes vehicle parking and storage space as well as a significant percentage of the outdoor covered space. Figure 6b shows the change in area of all buildings and roof square area in different plot density classes. Based on this, it is evident that vehicle parking and storage space comprise an average of 50 m^2 of impervious coverage.

As plot density increases, the difference between roof square area and building area seems to decrease very slightly.

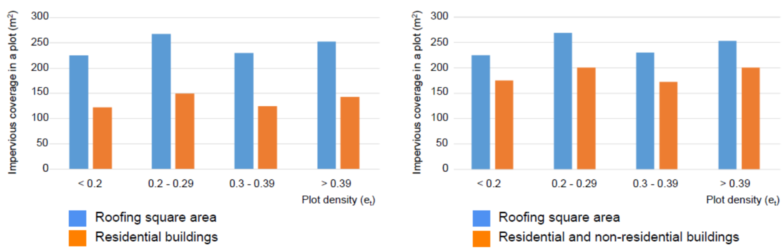

Figure 6a and 6b. Change in the roof square area in relation to the residential building area and area of all buildings with an increase in plot density.

The importance of gardens is highlighted when examining the impervious coverage of a single-family house plot as a whole (Figure 7). In the housing fair gardens, a large amount of paving stones and tiles are used in order to facilitate visitor movement during rainy conditions. As a result, the impervious coverage ratio does not directly correlate with the situation of other single-family house

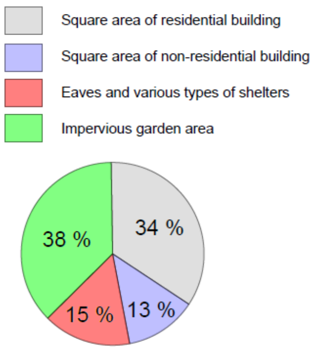

Figure 7. Average distribution of impervious surfaces in single-family house plots (N = 63).

areas. However, the housing fair gardens represent an ideal of what constitutes a good garden, so there is some justification for their analysis.

The study found that the garden of a single-family house accounts for the largest amount of impervious coverage within a plot. It is, on average, greater than that of the residential building area. If the garden, vehicle parking and sheds (outbuildings) are taken as a single entity where garden functions are concerned, the impervious coverage of the garden will account for over half of the average impervious coverage.

The impervious coverage of the garden is tied to the placement of buildings, their entrances and vehicle parking within the plot. The American and Australian discussion on the roles played by the front and back yard and changes in their surface coverage (Hall 2006; Stone 2004) does not, in and of itself, dovetail well with Finnish practices, where the building or buildings are clearly separated from buildings in neighbouring plots. The housing fair gardens even include solutions, in which the garage is placed at the back of the yard in a narrow plot, thus making the impervious coverage considerably more than if the garage were to be placed right off the street. Thus, building placement and the need for passageways determines the formation of impervious coverage during the drafting phase of the local detailed plan.

In a more detailed analysis of the above-mentioned averages in the impervious coverage of single-family house plots, Figure 8 shows that there is very wide variation in the percentage of impervious coverage in a garden. The error bar in the figure indicates the area between the minimum and maximum value, where the impervious coverage of a garden in a plot density class of less than 0.2 was 52 m^2 and 359 m^2 at either extreme. Although the impervious coverage of a garden varies in all plot density classes, it is extremely low in plot density classes over 0.4. In a densely-built single-family house area, garden sizes are essentially small, so it stands to reason that homeowners would not want to entirely cover such a small garden area.

As the housing fair gardens have a plot density class of 0.3-0.39, the area of other buildings, i.e. vehicle parking and storage space, does not include any covered area at all. It is interesting to note that increasing the plot density does not significantly reduce the area taken up by a garage or carport. If there is a desire to limit the amount of impervious coverage of single-family house areas in an increasingly dense urban structure, a stance must be taken regarding vehicle parking in covered structures. Indeed, in this respect, the housing fair concept might place greater emphasis on the result, as the garages and carports built for the fair are showcase venues for product presenters.

Covered outdoor space attached to the building, i.e. shelters, canopies and eaves, decreases as plot density increases beyond a plot density class of 0.2-0.29. On average, more covered outdoor space is designed and built in a plot density class of 0.2-0.29 than in other classes. This would suggest that, as the total area decreases, so too does the amount of covered outdoor space.

According to this study, the residential building area does not decrease along with plot density, but rather increases to a plot density of more than 0.4. The single-family house has been the preferred housing type for Finns due to the private garden it offers, which provides space for family activities as well as distance from the neighbours. Increasing the residential building area in the highest-density class results in a more frequent use of one-storey solutions and a shrinking of distances between neighbouring plots and their buildings. However, it must be kept in mind that only 5 plots had a plot density class of over 0.4 in this study, so there is not a large sampling of data for this class.

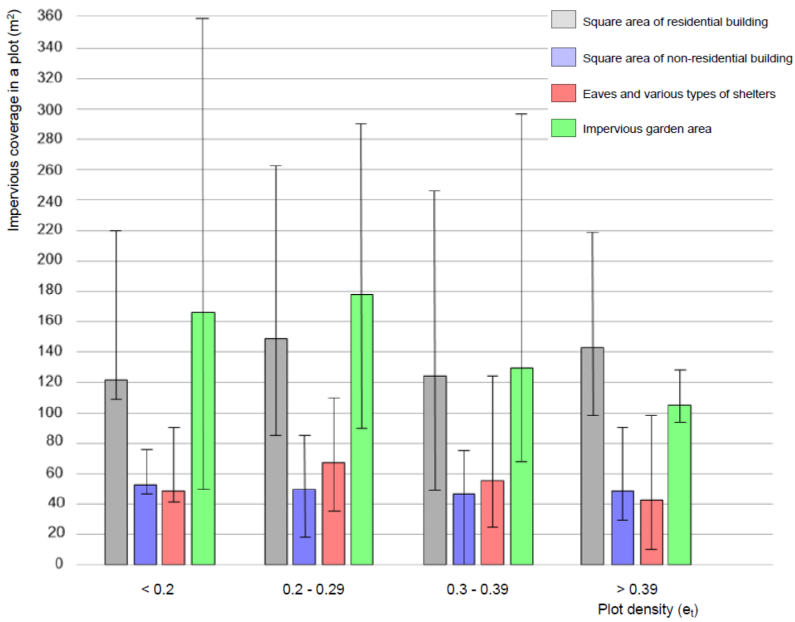

Figure 8. Division of impervious coverage in a single-family house plot in different plot density classes (as an average and as the range between the minimum and maximum value).

Pervious garden area

The pervious area of a garden allows for water absorption, water retention in the ground and facilitates the growth of vegetation in and around the plot. Pervious surfaces also include mineral aggregate surfaces, whose total coverage decreases as the plot density increases (Figure 9). One obvious place for mineral aggregates within a plot is the skirting around the building foundation. The purpose of the skirting is to ensure that no water-retaining substrates come into direct contact with the foundation. The use of pervious surfaces in these areas do not--or should not--include the function of water absorption. In the fair plots, mineral aggregates were also used in stormwater detention ponds placed in the middle of a block. These ponds are used in stormwater management. Cobblestones, gravel and crushed aggregates were used as surface coverings in the housing fair sites.

The vegetated environment of plots consists of lawns, landscaped areas and areas with preserved vegetation. In developing diverse vegetation, landscaped areas and areas with preserved vegetation play a key role. Even if the plan for a landscaped area were to only include just one or a few varieties, it would still have a substrate that retains water and nutrients, thus offering the potential for adding more varieties. Areas with preserved vegetation contain varieties growing there prior to their development. Maintaining substrate vitality brings endemic varieties to the area. In the study, areas with preserved vegetation were only found in individual plots and were completely missing from plot densities over 0.3 (Figure 9).

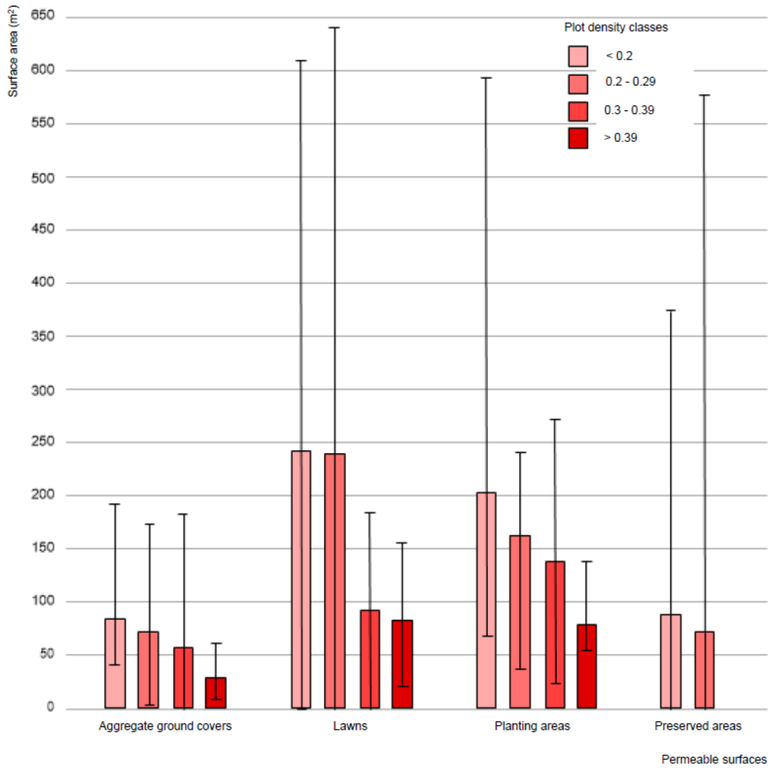

Figure 9. Change in pervious coverage in a single-family house garden in different plot density classes (as an average and as the range between the minimum and maximum value).

Although lawns are seen as offering very little in terms of biodiversity, with very few varieties represented, they do offer an important area for lounging and activity in the garden. Consequently, lawns are low in biodiversity value, but very important to social sustainability and diversity. Lawns also provide area for water absorption. The study found that lawns were used extensively in low-density plots, while lawns in plot density classes of less than 0.2 and 0.2-0.29 were, on average, slightly less than 220 m^2. On the other hand, the use of lawns is largely based on the preferences and choices of individual landscape planners, as the study includes numerous gardens that did not have any lawn at all as well as gardens almost entirely covered by lawn with single trees and bushes placed simply in scattered locations.

Conclusions

Single-family house areas will continue to exist in cities, regardless of the growth strategies being employed. The role that a single-family house area plays in creating urban green spaces or stormwater management depends on several factors during the implementation phase and even after it. Naturally, an individual plot in a single-family house area does not define the characteristics of the entire area, but when a majority of the plots adhere to limits set for, for example, the type and quantity of surfaces to be used, it becomes possible to reduce the formation of impervious coverage and, in turn, mitigate the cause of stormwater. At the municipal level, single-family house areas have the potential to both create privately developed urban green spaces and manage stormwater, both of which can be controlled by the percentage of impervious coverage in each plot.

This study found that 62% of the impervious surfaces in a Finnish single-family house plot is formed by the house itself and its eaves, canopies and other covered outdoor space. Just over half of this area is made up of the roof square area of the residential building. Regulation of the remaining roof square area should become a key area of focus in the management of imperviousness, also in Finland. In follow-up studies, particularly in practical design work, thought should be given to: a) the use of uncovered vehicle parking methods in densely-built single-family house areas; and b) the true purpose of recreational shelters in the Finnish climate. Regulatory measures for these might include limiting the total amount of roof square area and redefining the standard guidelines for garages and carports.

Thirty-eight per cent of the impervious coverage in a Finnish single-family house plot is found in the garden. Where the garden is concerned, the ability to use statutory land use planning for regulating impervious coverage in plots is focused on the central placement of the residential building and vehicle parking, thus reducing the use of unnecessary passageways.

The popularity of paving stones and tiles results in a considerable amount of impervious coverage. However, the use of paving stones and tiles stems from the need to move between different parts of the garden, provide additional vehicle parking or a turnaround within the plot, or create a foundation for a lounging area. Hard surfaces directly take pervious and, in many cases, vegetated environment away from the total garden area. Issuing a guideline concerning the amount of vegetation to be included within a plot is not, however, realistic, as the individual preferences of the plot users over time may change the surfaces into impervious ones. Promoting the amount and type of a vegetated environment, such as by doing away with intensively manicured lawns, requires a great deal of resident co-operation after statutory land use planning and construction.

If stormwater management is problematic in the planning of a certain area, such as where soil properties or drainage system dimensioning are concerned, statutory land use planning should make specification of the maximum area or percentage of all impervious surfaces in each plot a key statutory land use planning regulation. Reducing the amount of stormwater in these areas is of the utmost importance. Specification of the maximum area of impervious coverage also regulates the amount of urban green space within plots.

References

Arnold, C. & Gibbons, J. 1996, “Impervious surface coverage. The emergence of a key environmental indicator”, *Journal of the American Planning Association*, vol. 62, no. 2, pp. 243-258.

Cameron, R., Blanusa, T., Taylor, J., Salisbury, A., Halstead, A., Henricot, B. & Thompson, K. 2012, “The domestic garden – Its contribution to urban green infrastructure”, *Urban Forestry & Urban Greening*, vol. 11, no. 2, pp. 129-137.

Davies, Z., Fuller, R., Loram, A., Irvine, K., Sims, V. & Gaston, K. 2009, “A national scale inventory of resource provision for biodiversity within domestic gardens”, *Biological conservation*, vol. 142, no. 4, pp. 761-771.

EPA, 1993. Environmental Protection Agency, Guidance Specifying Management Measures of Nonpoint Source Pollution in Coastal Waters, 840-B-92-002.

Golding, J. 2007, "'Ecological land-use complementation' for building resilience in urban ecosystems", *Landscape and Urban planning*, vol. 81, no. 1-2, pp. 46-55.

Hall, T. A 2008, "Where have all the gardens gone?", *Australian Planner*, vol. 45, no. 1, pp. 30-37.

Krebs, G., Rimpiläinen, U-M. & Salminen, O. 2013, "How does imperviousness develop and affect generation in an urbanizing watershed?", *Fennia,* vol. 191, no. 2, pp. 143-159.

Loram, A., Tratalos, J., Warren, P.H. & Gaston, K.J. 007, "Urban domestic gardens (X): the extent & structure of the resource in five major cities", *Landscape Ecology*, vol. 22, no. 4, pp. 601-615.

Mathieu, R., Freeman, C. & Aryal, J. 2007, "Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery", *Landscape and urban planning*, vol. 81, no. 3, pp. 179-192.

Novotny, V., Ahern, J. & Brown, P. 2010. *Water Centric Sustainable Communities: Planning, Retrofitting and Building the Next Urban Environment.* Wiley, USA.

Perry, T. & Nawaz, R. 2008, "An investigation into the extent and impacts of hard surfacing of domestic gardens in an area of Leeds, United Kingdom", *Landscape and Urban Planning*, vol. 86, no. 1, pp. 1-13.

RT-kortti Rakennuksen pinta-alat. 2011. Rakennustietosäätiön RT-kortti 12-11055. [RT Building Information File, Building square areas].

Schuler, T. 1994, "The importance of imperviousness", *Watershed Protection Techniques*, vol. 1, no. 3, pp. 100-111.

Schuler T., Fraley-McNeal, L. & Cappiella, K. 2009, "Is impervious cover still important? Review of Recent Research", *Journal of hydrological engineering*, vol. 14, no. 4, pp. 309-315.

Sjöman, J. & Gill, S. 2013, "Residential runoff – The role of spatial density and surface cover, with a case study in the Höjeå river catchment, southern Sweden", *Urban Forestry and Urban Greening*, vol. 13, no. 2, pp. 304-314.

Stone, B. 2004, "Paving over paradise: how land use regulations promote residential imperviousness", *Landscape and urban planning* vol. 69, no. 1, pp. 101-113.

Suomen asuntomessut (2012) Kävijätutkimus, Asuntomessut Tampereella 2012. Rakennustutkimus RTS Oy. Available through: http://asuntomessut.fi/organisaatio/osuuskunta/messututkimukset/ [Accessed 13 May 2018]

Suomen asuntomessut (2013) Messututkimus, Asuntomessut Hyvinkäällä 2013. Rakentaja.fi. Available through: http://asuntomessut.fi/organisaatio/osuuskunta/messututkimukset/ [Accessed 13 May 2018]

Suomen asuntomessut (2014) Messututkimus, Asuntomessut Jyväskylässä 2014. Rakentaja.fi. Available through: http://asuntomessut.fi/organisaatio/osuuskunta/messututkimukset/ [Accessed 13 May 2018]

Suomen asuntomessut, toiminta-ajatus. 2016. Available through: http://asuntomessut.fi/organisaatio/osuuskunta/toiminta-ajatus/#main [Accessed 10 May 2018]

Verbeeck, K., Van Orshoven, J. & Hermy, M. 2011, “Measuring extent, location and change of imperviousness in urban domestic gardens in collective housing projects”, *Landscape and Urban Planning*, vol. 100, no. 1-2, pp. 57-66.

Vierikko, K., Salminen, J., Niemelä, J., Jalkanen, J. & Tamminen, N. 2014. Helsingin yleiskaava, Helsingin kestävä viherrakenne, Miten turvata kestävä viherrakenne ja kaupunkiluonnon monimuotoisuus tiivistyvässä kaupunkirakenteessa. Kaupunkiekologinen tutkimusraportti. Helsinki: Helsingin kaupunkisuunnitteluvirasto.

Paper 3

Tahvonen, Outi. 2014. Water for Vegetation – Knowledge Base for an Inte-grated Approach to Sustainable Stormwater Management in Site scale. Eclas2014 Conference, Landscape: A Place for Cultivation. Porto, Portugal, 2014, pp. 331-333.

III

Water for Vegetation – Knowledge Base for an Integrated Approach to Sustainable Stormwater Management in Site Scale

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stormwater management | green growth | skills | drainage system

Urban development mostly involves drainage. At the same time water represents the minimum factor of the vitality of urban green. Therefore a balanced approach between the practice of drainage and the infiltration orientated stormwater management is needed to improve practices that preserve the water in top soil available for vegetation. As a case, designs of a housing area in Southern Finland were studied to indicate the state-of-art in combining stormwater management practices with vegetation. It occurred that combinations are mainly implemented by standard practices that are based on vegetation (green roof, raingarden), but novel examples are lacking. Innovative and site-specific practices are built on knowledge base that covers both processes in plant growth and practices in construction and civil engineering. A knowledge triangle for the use of education in landscape architecture is represented.

INTRODUCTION

Sustainable stormwater management contains several concepts like Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS) and Water Sensitive Urban Design (WSUD). Despite the name of the concepts they all are aiming to manage stormwater locally, imitating natural water-cycles and providing multiple benefits (Novotny & all, 2010). Sustainable strategies are implemented by using Best Management Practices (BMP) for example grassed swales, raingardens or permeable paving (EPA, 2012). Integrated stormwater management starts from the earliest stages of planning and continues to site design combining technical, ecological and social aspects.

Sustainability is conventionally justified in SUDS concepts by combining both quantity and quality issues (Lee & Yigitcanlar, 2010) but here also vegetation involves the concept. For urban vegetation water is the lifeline as the urban habitat is built next to solid foundations and drainage constructions. A balanced approach between the practice of drainage and infiltration emphasized stormwater management promotes both healthy buildings and long-standing sustainability in built environment.

The complex urban context requires more than standard solutions in stormwater designs. The required knowledge base for implementing SUDS concepts as designs and construction details in site scale is discussed in this paper. The question is: what is the required knowledge base for urban stormwater design that enables integration of water into vegetation?

The pedagogical focus is set on the content of knowledge base, recognizing the fact that expertise is developing not only knowledge but also skills and attitude. Defining the knowledge base is the first phase of course planning followed by the choice of learning/teaching method, the assignment and assessment criteria.

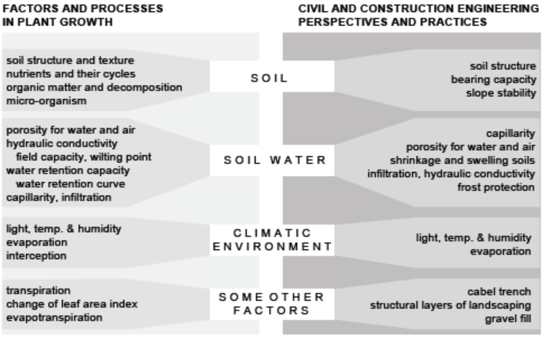

FIGURE 1. Water in urban context from the perspective of plant growth and civil and construction engineering.

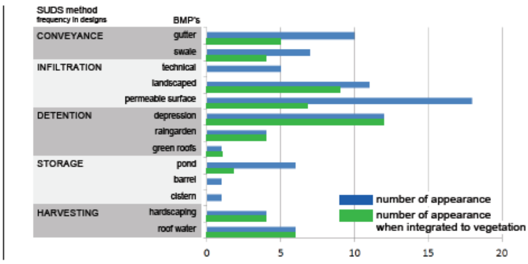

FIGURE 3. Plot scale stormwater management practices in Vuores Housing Fair 2012. Data includes garden designs (n=27) of single-family houses at the starting point of stormwater management chain.

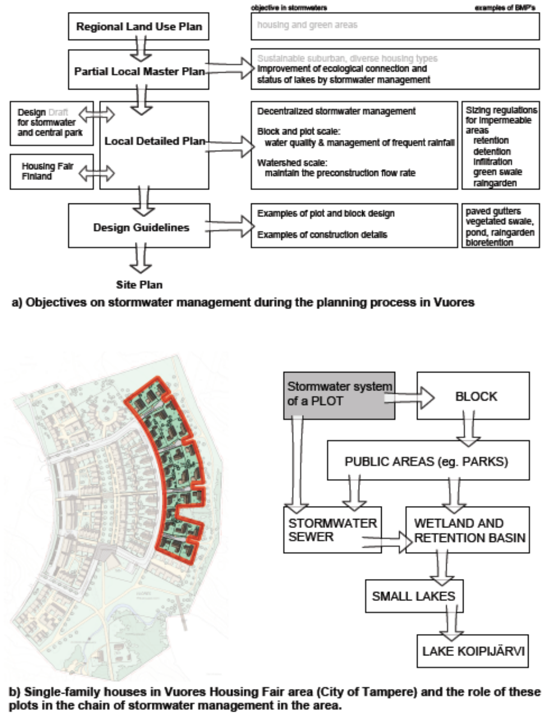

FIGURE 2. Objectives on stormwater management during the planning process in Vuores.

WATER AND VEGETATION IN THE URBAN CONTEXT

Urban green as a functioning part of ecosystem provides human health and well-being (Tzoulas et al, 2007). Arising concepts of green infrastructure and urban ecosystem services are dealing with urban green on a landscape scale. Urban context is a harsh environment for plant growth. Built environment is extensively based on earthworks, different foundations, subsurface drains and networks of cables and wires. Conventional urban drainage couples surface drainage with subsurface drainage systems that are designed to convey stormwater effectively (Aronica & Lanza, 2005). As civil and construction engineering are designing a solid foundation and well-drained constructions, water and nutrient stress are considered to be the most common problems in urban vegetation (Beatty & Heckman, 1981; Iakovoglou et al., 1981).

Landscape architecture's use of vegetation applies some technologies of agriculture and engineering. In education it is an advantage to provide perspectives on both disciplines instead of one-sided interpretation. Figure 1 outlines some examples of different approaches to same topics of urban context in water.

CASE

The Vuores area in Tampere, Southern Finland is represented as an example for linkage of different scales in stormwater management and demonstrating the state-of-practice of knowhow in plot scale designs to integrate vegetation into stormwater management.

Housing Fair Finland and the City of Tampere organized a housing fair in 2012 in part of Vuores. The theme of the fair was sustainable city living and there was a focus on stormwater management in all scales and during the whole planning process (Figure 2 a). The housing fair area is a part of new development outside the city center and it is forming a major example for sustainable stormwater management on a national level. The master plan for stormwater management, drawn up by Atelier Dreiseitl, interacted with the planning process (Figure 2 a).

Plots of single-family houses in the housing fair area were studied and the chain of stormwater management was identified in the area. All 27 designs implemented (Figure 2 b) were studied to define the applied sustainable drainage methods and to identify the solutions for integrating stormwater management and vegetation. Solutions were classified in this study into five categories (Figure 3).

The result demonstrates the range of practices used in stormwater management in the Vuores housing fair area. In average three out of thirteen BMP's were used in a plot and thereby combinations of several BMP's were scarce.

The result also gives an idea of the practices that are currently integrated with vegetation by designers. Stormwater management can be seen in a persistent role in Vuores planning process and guidelines, but implementation is providing only few examples of storage and stormwater harvesting. Furthermore integration of

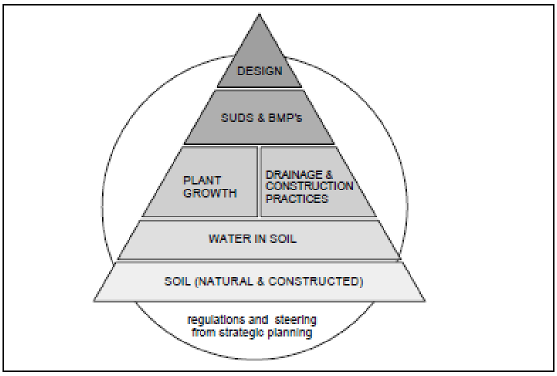

FIGURE 4. . Knowledge base for adaptive skills to integrate water and vegetation in sustainable stormwater management.

water with vegetation is not realized, consequently water might be seen as a nuisance that is taken care off only by new methods.

Raingardens, green roofs and depressions are shown in BMP's as vegetated examples consequently these solutions are also in Vuores integrated to vegetation. Noteworthy gutters, permeable pavers and ponds are designed only for conveyance, infiltration or storage without making it useful for vegetation.

DISCUSSION

This paper reviews the components of integrative knowledge base in stormwater management. Sustainable concepts need to penetrate all the levels from planning to detailed construction to fulfil the integrative and innovative stormwater management.

At the site scale stormwater management needs to be realized as unbroken treatment chains and applied constructions that are 1) integrated into the form and space, 2) arranged carefully in between foundations and drains of construction, and 3) providing necessary water for vital vegetation growth.

Education in sustainable stormwater management should not only be based on copying separate BMP's but rather on constructing a solid knowledge base for capability to apply, modify and retrofit standard BMP's to site specific conditions.

A proposal for the knowledge base (Figure 4) includes 7 components to consider in forthcoming course planning in Landscape architecture.

Properties of soil and soil water can be seen as fundamental knowledge base in sustainable stormwater management. Balance between the technical and the vegetative approach is needed to ensure the capability to realize different needs for constructions and plant growth. After realizing this context different BMP's should be applied and modified to site specific conditions and to the overall design in site.

This knowledge base can be covered also by starting with design and only later focus on the bottom of the pyramid, but that is the question for the teaching method and the assignment.

REFERENCES

Aronica, G.T. and Lanza, L.G. (2005), '*Drainage efficiency in urban areas: a case study*', Hydrological Processes. 19/5: 1105-1119;

Beatty, R.A. and Heckman, C.T. (1981), 'Survey of urban tree programs in the United States', Urban Ecology 5/2: 81-102;

EPA, United States Environmental Protection Agency, '*Best Management Practices (BMPs)*' website http://www.epa.gov/nrmrl/wswrd/wq/stormwater/bmp.html, accessed 1 April 2014;

Iakovoglou, V., Thompson, J., Burras, L. and Kipper, R. (2001), '*Factors related to tree growth across urban-rural gradients in the Midwest, USA*', Urban ecosystems 5: 71-85;

Lee, S. and Yigitcanlar, T. (2010), '*Sustainable urban stormwater management : water sensitive urban design perceptions, drivers and barriers*', in Yigitcanlar, T. (ed), Rethinking Sustainable Development : Urban Management, Engineering, and Design. Premier Reference Source. IGI Global, Engineering Science Reference, United States of America, pp. 26-37;

Novotny, V., Ahern, J. and Brown, P. (2010), *Water centric sustainable communities*, Planning, retrofitting, and building the next urban environment. (New Jersey: Wiley);

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kazmierczak, A., Niemelä, J. and James, P. (2007), '*Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review*', Landscape and Urban Planning 81/3: 167-178.

Paper 4

Tahvonen, Outi. & Riihimäki, Mona-Anitta. 2016. Urban Vegetation for Bio-retention in Cold Climate – A Short Interval Flooding Test in Finland. Eclas2016 Conference, Bridging the gap, Rapperswil, Switzerland, pp. 497-500.

The appearance of this article differs from the original publication due to readability of the figures.

IV

Urban vegetation for bioretention in cold climate – a short interval flooding test in Finland

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ABSTRACT

Bioretention is a method integrating storm water management and vegetation in decentralized solutions in the form of raingardens and swales. Vegetation of a bioretention cell improves water infiltration, but by careful plant selection it can also provide a design element for urban space. In this study a short interval flooding test was conducted to study how urban vegetation stand these conditions. The selected 15 species had three treatments: a) a control group in good nursery maintenance, b) plants in standing water for 3 days and then 6 days without irrigation and c) plants in standing water for 6 days and then 6 days without irrigation. The cycles were repeated through summer 2015. Plants were measured by size index, shoot and root system dry weight before and after the treatment. Visual features were mapped during the whole experiment. Generally the plants survived surprisingly well in these extreme conditions, and mortality was low. *Sorbaria sorbifolia, Syringa vulgaris* and *Acer platanoides* did not stand well the changing conditions. *Geranium macrorrhizum, Ribes alpinum and Ribes glandulosum* suffered.

keywords: (5) urban vegetation, plant selection, raingarden, stormwater, flooding

INTRODUCTION

Recent debate on sustainable storm water management combines qualitative, quantitative and amenity aspects in the urban environment. American Low Impact Development (LID), European Sustainable Urban Drainage System (SUDS) and Australian Water Sensitive Urban Design (WSUD) are all supporting decentralized and multifunctional storm water management (Novotny, Ahern & Brown, 2010). Whichever way this new approach is called, it contains an idea of mimicking natural water cycles to prevent urban flooding, to improve local infiltration and to introduce urban design dealing with rain water.

The general characterization of sustainable storm water management practices emphasizes multifunctional water management. One construction is expected to support several processes. Bioretention is a practice combining evapotranspiration, purification, detention and infiltration. These processes are provided by construction of several layers of sands and gravel, living soil and vegetation. Raingardens, bioswales and bioretention cells are based on bioretention. (Roy-Poirier, Champagne, ASCE & Filion, 2010).

A bioretention cell collects surface runoff in a shallow, vegetated depression. The ponding area storages and evaporates water, and slowly infiltrates the water into different construction layers and percolates to ground water or, if necessary, conveys additional water to further sites by subsurface drainages. Construction layers filtrate water and remove some of the nutrients and pollutants to improve the quality of storm water. Growing conditions in a bioretention cell alternate between extreme drought and standing water as the drainage layers ensure water extraction, but surface design's purpose is to collect water.

Vegetation has a clear role in a bioretention cell. Vegetation moves water through evapotranspiration, and is capable of nutrient uptake. The root system supports infiltration by forming macropores in the soil and also provides an environment for invertebrates to further support macropore formation. Vegetation in bioretention cell can provide the same benefits as other urban vegetation does: as architectural and visual element in urban design, and improvement of microclimatic conditions. (Davis, Hunt, Traver & Clar, 2009; Hunt, Lord, Loh & Sia, 2015).

In cold climate frost, repeated melting, deicing chemicals and suspended solids in melt water require special attention in bioretention specifications. The type of frost defines the capacity of hydraulic conductivity. If a large grain size is preferred, the frost is granular and hydraulic conductivity remains through the winter, but the structure may dry out during dry weather and vegetation suffers from drought. Then fine grain size supports vegetation in the growing season, but may form concrete frost that both prevents infiltration and breaks roots by freezing water.

This paper aims to clarify what plant species, usually used in a cold climate, cope the conditions of a bioretention cell.

MATERIALS AND METHODS

The research design follows the idea of short interval flooding test presented by Dylewski, Wright, Tilt and LeBleu (2011) and Jernigan and Wright (2011), where plant species in containers are first in standing water and then totally without irrigation for certain repeated time periods. This arrangement follows the conditions that are typical in a bioretention cell.

Plant selection was defined in several stages and categorized into three groups: plants that are known to tolerate different moisture conditions, plants that are typically used in built environment, and plants that might tolerate the conditions. Plant species in these categories were commented by partners in Helsinki, Espoo and Vantaa municipalities, by the association of landscape designers and landscape architects in Finland and also by landscape constructors. The final selection (Figure 1) ensured plants for different vegetation layers (groundcovers, small shrubs and large shrubs/small trees).

Experiment plants were pre-cultured in a greenhouse to ensure a strong root system and vital growth before the actual treatment. Root systems were washed and plants replanted in identical soil in 3 litre containers. The preculture phase started 6th of May 2015 and continued until 1st of June, and during this time the plants had good care following typical professional practices in horticulture, such like fertilizing, irrigation and pruning to form uniform and vital plants.

A short interval flooding test was organized outdoors but under shelter. In this arrangement plants faced typical local weather and were adapted to temperature, air humidity and wind conditions. After preculture all experimental plants were placed outdoors and receiving good care for one week before flooding treatment begun. Experimental design followed randomized completed block design with 15 taxa.

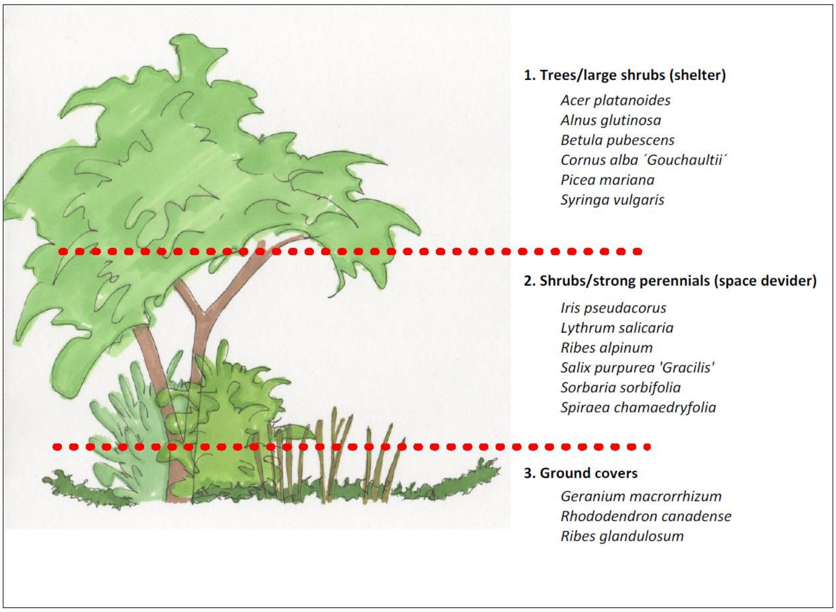

Figure 1: *Plant selection combined views of local professionals in green industries and balancing between different visual functions that the plant combination may provide.*

Experimental plants were divided into three groups that had different treatments. The first group had good nursery maintenance, the second was under standing water for 3 days and then 6 days totally without irrigation and the last one was under standing water for 6 days and then 6 days totally without irrigation. There were 15 taxa and 5 plants in every treatment, and edge plants in every block were not included in experimental plants.

Standing water for flooding days was organized by placing the experimental plants in 3 litre containers into 6 litre containers and then adding water to the outer container. The water level was kept at the top of soil surface for the whole flooding period (Figure 2). Water level was monitored once a day. The treatment of good nursery care and edge plants were irrigated as needed.

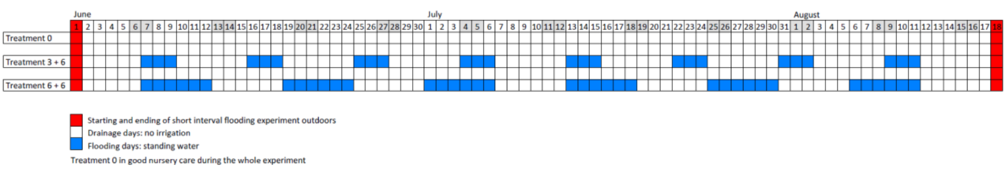

Figure 2: *Cyclic flooding periods in summer 2015. Good nursery care was provided for all plants during the first outdoor week. Experiment was carried out under a shelter.*

Experimental plants were measured before and after treatment by size index (SI) [(height + widest width + width perpendicular to widest width) / 3] introduced by Dylewski and others (2011). Also root system and shoot dry weight was measured on 5 plants in every taxa before and from all the plants after the treatment. All plants, both roots and shoots, were photographed at the end of the experiment to provide a possibility for visual comparison between different treatments.

RESULTS AND DISCUSSION

Overall mortality was low in this experiment, and it was observed in some plants of *Acer platanoides*, *Geranium macrorrhizum*, *Ribes glandulosum*, *Ribes alpinum* and *Lythrum salicaria*. *Geranium maccrorrhizum* and *Acer platanoides* suffered from standing water and *Lythrum salicaria* from long unirrigated periods. The change of visual condition between treatments was found in all species, but it was observed to be clear in *Cornus*, *Spiraea chamaedryfolia*, *Acer*, *Sorbaria sorbifolia*, *Lythrum, Geranium, Ribes alpinum* and *Ribes glandulosum*. Good visual condition was observed in *Salix, Iris pseudocorus, Alnus glutinosa, Picea mariana, Betula pubescens* and *Rhododendron canadense*. Cyclic flooding had no effect on the visual condition in *Alnus glutinosa* and *Iris pseudocorus*.

The changes in SI support visual observations (Figure 3). All plants in the treatment of good nursery care had strong growth, but the differences between good care and the flooding treatments were clear. According to these results flooding effects the SI in two ways. There is decrease of SI between good care and 3+6 treatments that still decrease to 6+6 treatment, or the lowest SI occur in 3+6 treatment. This finding indicates that plants typically flourishing in wet conditions might not thrive in continually changing conditions. *Ribes, Geranium, Acer* and *Syringa* are the weakest survivors based on the change in SI. Other species can be considered for bioretention vegetation.

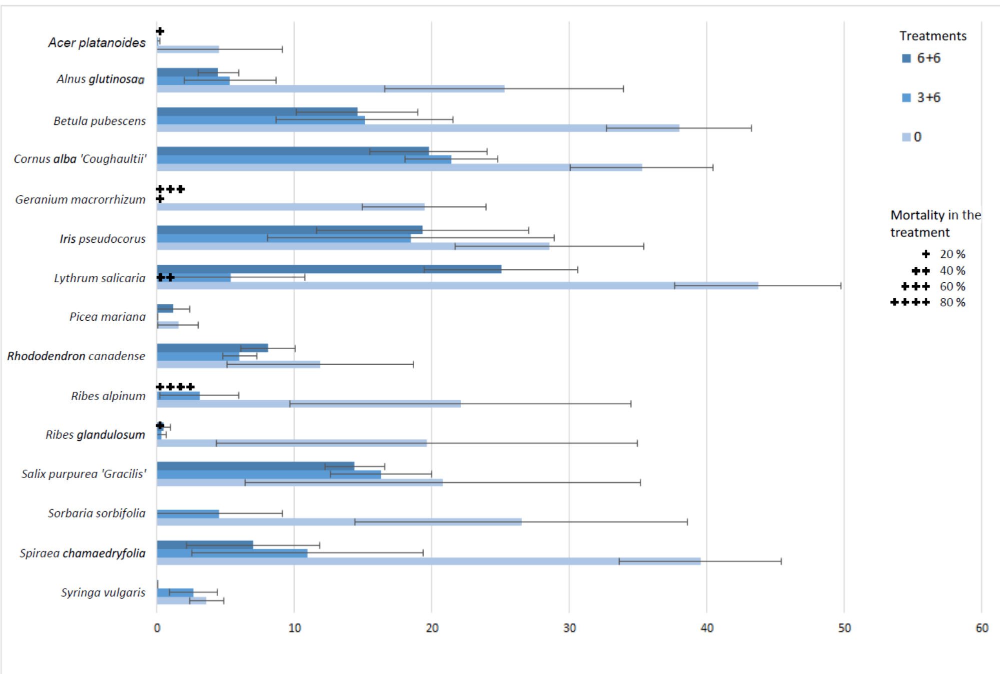

Figure 3: *The change in SI in different treatments.*

The flooding period of 6 days is exceeding most recommendations of the maximum flooding period. Guidelines often define the maximum time for ponding, but the maximum dry period is of course not known. This requires plant selection that withstands standing water but flourish in more dry conditions.

The planting design of bioretention should include plants in several layers to support efficient evapotranspiration and infiltration through macropores. This experiment introduces some plant species of different layers to stand the changing conditions of bioretention in urban context.

This research continues to define proper construction depth and materials of bioretention cells for Finnish practices in 2016.

REFERENCES

Davis, A., Hunt, W., Traver, R. & Clar, M. (2009). Bioretention Technology: Overview of Current Practices and Future Needs. Journal of Environmental Engineering, 109-117. SpringerOpen.

Dylewski, K., Wright, A., Tilt, K. & LeBleu, C. (2011). Effects of Short Interval Cyclic Flooding on Growth and Survival of Three Native Shrubs. HortTechnology, 21, 461-465.

Hunt, W., Lord, B., Loh, B. & Sia, A., (2015). Plant Selection for Bioretention Systems and Stormwater Treatment Practices.

Jernigan, K. & Wright, A. (2011). Effect of Repeated Short Interval Flooding Events on Root and Shoot Growth of Four Landscape Shrub Taxa. Journal of Environmental Horticulture, 29, 220-222.

Novotny, V., Ahern, J. & Brown, P. (2010). Water centric sustainable communities: planning, retrofitting and building the next urban environment. Wiley, USA.

RoyPoirier, A., Champagne, P., ASCE, A.M. & Filion, Y. (2010). Review of Bioretention System Research and Design: Past, Present and Future. Journal of Environmental Engineering, 136, 878-889.

Paper 5

Tahvonen, Outi. 2018. Adapting Bioretention Construction Details to Local Practices in Finland. Sustainability, 10, 276.

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Adapting Bioretention Construction Details to Local Practices in Finland

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Received: 18 October 2017; Accepted: 19 January 2018; Published: 23 January 2018

Abstract: Bioretention is a method of storm water management that includes several processes following the natural hydrological cycle. Bioretention, or variations of it, include rain gardens and bioswales, infiltrates, filtrates, evapotranspirates, and help to store and manage storm water run-off. A bioretention cell retains water, removes pollutants, and provides water elements for urban green areas. Although bioretention is a promising method for multifunctional storm water management, its construction details should not be copied from other climatic areas. A direct application may dismiss local conditions, materials, and construction practices. This study aimed to adapt construction details for bioretention to Finnish local practices and conditions and to formulate bioretention constructions that balance water, soil, and vegetation. First, construction details were reviewed, then local adaptations were applied, and finally, the application and two variations of growing media in two construction depths were tested in a test field in Southern Finland. Sandy growing media allowed the efficient retention of water during the first year, but failed to provide vital growth. The use of topsoil and compost in the growing media improved growth, but held high electrical conductivity after infiltration. All the experimental cells in the test field showed activity during the melting periods, both during winter and spring. If bioretention plays a multifunctional role in urban design and engineered ecology, the design parameters should not only focus on storm water quantity, but also on quality management and vegetation growth.

Keywords: bioretention; storm water management; test field; growing media; heavy rain simulation; vegetation cover; cold climate

1. Introduction

Urbanization, particularly urban densification, has increased the proportion of impermeable surfaces to precipitation. Precipitation and surface runoff have fewer possibilities to infiltrate, and the natural water cycle is disturbed. Furthermore, climate change has transformed local conditions so that annual precipitation has remained at the average level while heavy precipitation events have intensified [1]. The increase of impermeable surfaces and climate change mean that cities must study and apply new approaches to storm water management.

Sustainable urban drainage (SUDS), and other related concepts such as low impact development (LID) and water sensitive urban design (WSUD) have focused on this new type of storm water management [2]. SUDS applies to urban design, amenities, community enhancement, and vegetation as well as conventional quality and quantity management. Best management practices of these concepts enhance the visible water surface, detention, and slow infiltration after a rain event. Moreover, SUDS provides the possibility to enhance community-based activities, public participation, and the proportion of urban green.

Bioretention is one of the best management practices in SUDS. It is a method that seeks to infiltrate, retain, and filtrate storm water through a surface basin, constructed soil layers, and vegetation. This construction mimics the natural water cycle and is designed to reduce runoff volume, delay peak flow, and improve water quality. Vegetation has an essential role in bioretention as the root system improves infiltration while shoots and foliage promote interception and evapotranspiration. Although bioretention was developed to address storm water management, it also functions as an architectural element in urban design and creates a diverse habitat for green infrastructure in urban environments.

The urban environment generally provides harsh conditions for vegetation. The built environment is efficiently drained to keep surfaces dry and to prevent pools. The construction of built-up areas in Finland is based on frost and moisture protection by earthworks and introduces frost-resistant mineral soils, anti-capillary gravel, subsurface drainages, and thermal insulation plates [3]. These practices make very dry growing conditions for plants as the water is drained away. Dry growing conditions exist next to buildings, but are also near driveways, parking lots, patios, and walls. Simultaneously, the requirements for growing remain unchanged. Vegetation requires water, soil, nutrients, light, and a suitable temperature for growing. Water and nutrient stress are considered to be the most common problems in urban vegetation [4,5].

Concurrently, both a water surplus and drought affects urban vegetation. The solution for this challenge is not simple, as the quantity of water is not distributed evenly, but occurs as single large events. Vegetation, with the exception of wetland plants that endure anaerobic conditions, drown in standing water [6]. Furthermore, general drainage in the built-up environment increases the drought between rain events. These problems, along with uneven distribution of water, might be partly solved with vegetation integrated storm water management practices such as bioretention.

The multifunctional nature of bioretention is interesting for the idea of sustainable and compact cities. The applications of bioretention such as bioswales and raingardens, function on several scales and sites, form urban spaces, serve as a functional part of storm water management, and offer a platform for social activities in a neighborhood. Thereby, bioretention has a multi-functional nature that promotes the efficient use of space in dense cities and is an appropriate design element for urban areas.

This study aimed to develop construction details for bioretention that are applicable to Finnish conditions. These local conditions include a cold climate with an annual precipitation of 680 mm, and construction practices are based on efficient drainage and frost protection. The application of bioretention aims to include the sustainable use of materials and vital vegetation for a balanced approach between water, soil, and vegetation. The research questions were:

(1) How should bioretention be constructed in a Finnish context in general? And specifically:

    What kind of growing media provides both sufficient storm water management and suitable growing conditions for vegetation?

(2) How does this construction function during the first year for: (a) storm water quantity management; and (b) vegetation growth?

This study was undertaken in three phases to answer these questions. First, a brief review on the construction details identified the essential elements, materials, and functions in bioretention. Second, the possible variations in the construction details were defined in a Finnish context. Third, these variations were applied in a test field. A comparison of two different construction depths and two different mixtures of growing media answered the first question on a mesocosm scale (surface area of 5 m × 5 m). The answer for the second research question relied on monitoring the function in the test field after both construction, during the first winter, and after irrigating the cells to simulate a heavy rain event. Furthermore, the growth of the plant community was observed by the change in vegetation cover. This paper reports on the construction details and the results of the test field functioning after the implementation phase from a test field where different growing media and construction depths were monitored together with vegetation cover in comparable conditions.

2. Bioretention

2.1. Appearance

The appearance of a bioretention cell may vary from sharp edged planters next to streets to free forms of raingardens. In any case, bioretention is located in the low parts of the topography, forming a vegetated depression. Specifically, vegetation provides the possibility of integrating bioretention in urban design. Multi-layered vegetation evapotranspirates efficiently, but it is also a design element to make enclosures, frame the views, form a gradient, rhythm, barriers, and foci [7]. In general, SUDS are multi-functional in nature, meaning that they integrate storm water quality and quantity management to amenity and biodiversity goals in an urban context.

Echols and Pennypacker [8] classified the utility goals and the amenity goals of storm water management. Although they identified these goals for all types of storm water management practices, the amenity goals—like education, recreation, safety, public relations, and aesthetics—can be specifically applied to bioretention. Later, Backhaus and Fryd [9] developed criteria to evaluate the visual appearance and aesthetics of storm water projects that concentrated on the choices made during the design process. Infiltration causes a challenge when assessing bioretention and its amenity or aesthetics [8]. Infiltrated water is not visible, therefore, the connection to water is visible mainly through the existence of vegetation.

2.2. Functions and Processes in a Bioretention Cell

As stated by Davis et al. [10], the functions of bioretention follow flow and mass balance. The flow balance includes the inflow and outflow of the amount of water as well as the processes that function within a bioretention cell such as vegetation evapotranspiration. Within a bioretention cell, two main processes for quantity management occur: retention and infiltration. The main elements of water retention are the ponding area and pore volume in the construction layers. This storage provides retention capacity for the entire structure. At the bottom of the construction layers, water infiltrates into the subsoil and continues as baseflow or percolates to groundwater. The infiltration depends on the quality of the subsoil. Subsoils with fine components only allow for slow infiltration. In some cases, for example, close to building foundations or areas at risk of groundwater problems, the details of the construction layers may prevent complete infiltration in situ, and the drainage layer may instead convey the water to further sites for infiltration.

Quality control relies on different treatment and accumulation processes. Filtration, sedimentation, adsorption, plant uptake, and microbial degradation remove and degrade pollutants that are dissolved into storm water run-off from urban surfaces. The urban run-off may contain suspended solids, heavy metals, nutrients, hydrocarbons, and pathogens as the most common pollutants. The bioretention construction and its materials can be modified against the known pollutants to improve the capacity for pollutant removal.

The ecological functions and processes in bioretention have been receiving increased attention. Levin and Mehring [11] studied how bioretention systems restored man-made ecosystems to maintain biodiversity, provide wildlife habitats and corridors, and pollination services. This maintains the idea of viewing the biota of bioretention cells as dynamic and successional living units.

2.3. Construction Details

The bioretention design details use several soil layers with several functions. Performance is dependent on the construction including vegetation [12–15], ponding depth [16–18], the soil media composition [19–21], use of geotextiles [22], and media depth [16,21]. The main layers in bioretention provide filtration, retention, infiltration, and growing conditions for vegetation. Figure 1 presents a schematic diagram of bioretention that follows the most commonly used construction layers.

There are several disciplines studying bioretention, and therefore the approach to bioretention vary from technical water engineering for quantity or quality concerns to urban biodiversity studies.

Figure 2 summarizes some of the multidisciplinary research concerning details in different construction layers in general and in cold climates. Construction details for cold climate focus on limitations of nutrient removal [23], dimensioning [24], material specifications [12,25,26], and the functioning of coarse [12,24,26,27] and fine grained growing media [28,29]. The aim of this summary was to provide the necessary knowledge for practical implementation, and to stress the balance between water, soil, and vegetation.

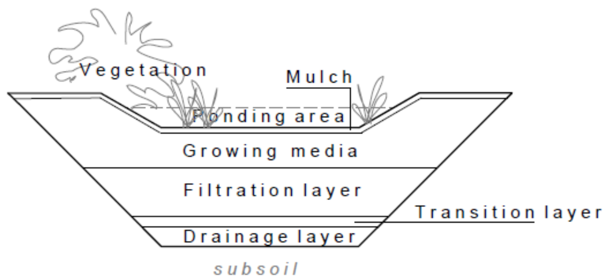


Figure 1. Schematic diagram of bioretention and its construction layers, modified from Hunt and Lord [30] and Davis et al. [31].

	CONSTRUCTION DETAILS IN GENERAL	SPECIFIC CONSIDERATIONS IN COLD CLIMATE
VEGETATION	***Forms the visible and living element*** that: Improves nutrient uptake, evaporation [13,14] and percolation [15]. Slows down the surface flow and filters sediments [13] Maintains permeability by thick roots [16] and Improves microclimate [17]. However, the growing conditions vary from standing water to drought requiering special consideration for plant selection and planting design.	Vegetation dormancy, salt and low temperature limit nutrient removal efficiency [25].
PONDING DEPTH	***Provides short-term storage volume prior to infiltration***. Maximum ponding depths vary between 10 and 30 cm in field studies [18] and the maximum pondig time varies from 24 to 96 hours [19, 20].	Snowstorage effects on sizing [26].
MULCH	***Supports plant growth and accumulates pollutants.*** Protects the surface from erosion. Reduces weeds, retains moisture for the use of vegetation. The quality of mulch effects on infiltration capacity and pollutant removal.	Organic mulch rather than aggregates [14] used thickness 7.5 cm [27], and 5 cm [26].
GROWING MEDIA	***Balances between vegetation growth and infiltration capacity.*** Follows two main recipes for the soil mixture: A) Engineered sandy soil; B) Topsoil-sand-composti. Clay content adjusts the hydraulic performance, supports the growing conditions by retaining moisture and nutrtitions, and provides cation absorption for pollutant removal. Recommendations from no fines (washed sand) [21] to 5 - 10% [20,22]. Organic matter promotes vegetation growth and microbiological activity, buffers pH, increases sorption, improves soil structure and microbiological activity. Recommendations from 1.5 % to more than 10 % by mass [23].	Recommendation to use coarse engineered soil [14, 26, 28, 29]. Khan et al. [30] and Roseen et al. [31] found that fine graded soils porvided also good functioning. The moisture in the soil may freeze, block soil pores, and reduce infiltration rate [26]. Cold climate requires coarser media to prevent concrete frost [25, 26].
FILTRATION LAYER	***Ensures hydraulic conductivity and filtration.*** Consist of filter sand without fines or organic matter.	
TRANSITION LAYER	***Seperates layers with different grain sizes.*** Replaces geotextiles that cause clogging risk [24].	
DRAINAGE LAYER	***Ensures a route for filtrated water or drainage to further sites.*** is not needed in sandy soils	Bioretention should have a drain in cold climate [28].
MEDIA DEPTH	***Defines the volume for water storage but also the need for earthmoving.*** Media depth varies between 50 and 120 cm in field studies [18]. Guidelines recommendations vary from German 10-30 cm to UK 100-150 cm [24].	

Figure 2. Construction layers and their details in general and the specific considerations in cold climates.

Laboratory experiments tend to use multiple soil layers and materials [14,32] and often lack vegetation, while field experiments are based on simplified construction layers with vegetation, but might lack the possibility of comparability [12,19]. The main concern regarding the balanced vegetation, soil, and water approach seems to be the growing media that functions as an interface between the vegetation growth and water infiltration [31]. The growing media should infiltrate the efficiently runoff volume for the needs of water quantity management, but for vegetation growth, it should hold water for later use in dry periods. Furthermore, storm water quality management generates contrasting aims in growing media and its nutrient content. A bioretention cell should not leach nutrients as they are needed for growth. The proportion of clay and organic matter are the key parameters for a balanced approach in growing media [22].

Organic matter forms through an amendment of compost or peat, and therefore decomposes over time. Decomposition subsequently causes the leaching of nutrients and pollutants. At the same time, organic matter is an important carbon source for micro-organisms that support bioretention functions and provide water holding capacity for the growing media. As Ewing [20] determined, some ambiguity exists in the guidelines defining the proportion of organic matter, but it is not always clear if the guidelines define the proportion of organic matter either by volume or by mass.

Organic matter is a topic that also varies in the recommendations for the use of topsoil in growing media. The use of topsoil aims to include local materials and the possibility of adding biologically active soil to the growing media. However, the detailed specifications for topsoil are impossible to describe as the qualities vary from site to site and from one country to another.

The hydraulic performance and retention time can be adjusted by the clay content. Too high a proportion of clay reduces soil permeability and soil pore size, which reduces the retention capacity of the whole system. Additionally, the high clay content causes surface cracking during dry weather, and these cracks provide a bypass for the treatment layers as the first run-off gathers in the ponding areas.

Vegetation plays an essential role in bioretention, although the growing conditions vary significantly between drought and standing water. Bioretention is not intended to be used as a wetland, and the bioretention cells are too dry for many wetland plants. Bioretention is designed to receive runoff, and therefore the vegetation must be able to withstand brief periods of inundation. Dryness depends on the water volume that it receives, how quickly the garden drains, and how frequently it rains. Rain gardens are wet only during and immediately after rain events [30].

Paus and Braskerud [12] divided planting strategies into two main approaches. The first is a traditional park design with a high maintenance requirement, and the second is a natural design adapted to local conditions. This kind of classification addresses the idea of new ecosystems that are human-built, modified, or engineered patches within the urban matrix [11]. A bioretention cell and its vegetation should provide hardy and long-lived vegetation for the urban environment.

3. Materials and Methods of Experimental Test Field in Lepaa, Finland

We developed two bioretention construction details to be implemented and compared in a test field. These two variations differ in the specification of growing media and total construction depth (Figure 3). One of the main objectives was to arrange conditions that allowed the practical construction challenges to meet and provide sufficient space for establishing vegetation communities.

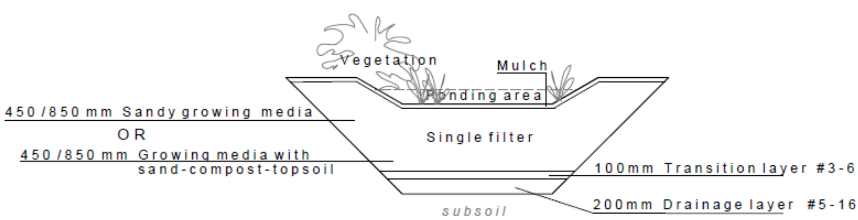


Figure 3. The layers used in this study. Altogether, the test field contained five cells. Two cells were 120 cm deep and the other two were 80 cm deep. All of them had a 20-cm maximum ponding layer on top of these layers. The fifth cell was an 80-cm deep sand filter as the control for the research design.

3.1. Finnish Conditions

Climatic conditions in Finland are typical of cold climates. Due to the Gulfstream, the temperatures in Finland are higher than the geographical location would indicate. Monthly averages range from −9.3 °C in January to 15.6 °C in July. Annual precipitation ranges between 500 and 650 mm. Snow covers the southwest corner of the country for three to four months, whereas the northern parts are covered for seven months [33]. The frost line in clay soils reaches a maximum of 100 cm in Southern Finland, but on average stays below 40 cm [34].

The impact of climate change will increase the average temperature 1.5–2 times faster in Finland than the global average [35]. In the future, temperatures—especially in the winter—are expected to increase, prolonging the growing season, and more rain instead of snow is expected [1]. The period for snow coverage will shorten and the frost in soil will decrease. The probability of heavy rainfall will increase throughout the seasons, and by the end of this century, only Northern Finland will have snow coverage [36].

New developments concentrate on a few city regions in Southern Finland, and 90% of housing production was located in the 14 biggest city regions in the country in 2015 [37]. As the new developments in the growth centers already occupy moraine and gravel soils, the ongoing housing construction is forced to move towards clay soils. This defines the foundation requirements for buildings, but also for landscaping and provides possibilities for infiltration.

Aggregates constitute the basis for construction materials such as concrete and asphalt, which are used for groundwork and as drainage elements for streets, roads, and buildings. They are also an essential part of landscape construction in green areas. Finnish aggregates originate from bedrock, ridge formations, and recycled materials. In certain areas, like the province Uusimaa where the growing metropolitan areas are located, nearly all ridge-based aggregates are already used for other purposes or are important for ground water resources. This means that aggregates need to be based on bedrock or be transported from a distance outside the province [38].

The use of peat and peat production in Finland differs from Central European practices and values as peat production and use has been traditionally used for 125 years. The main proportion of peat production is used for energy and about 10% is used for horticulture, landscaping, and other purposes. As a growing media or amendment, peat provides good value for its water holding capacity and is a sterile source of organic matter [39]. However, peat production affects the environment in terms of changes to the landscape, watershed qualities, dust emissions, and noise. The use of peat is also being discussed in light of carbon emissions and its potential as a renewable resource. Recent dichotomy in the debate concentrates on the effect to the political economy, the economic potential of peat land resources, the effects of peat production for water systems, and national energy self-sufficiency.

3.2. Development of Construction Details and Growing Media to Local Conditions

There have been a few bioretention studies in Finland that have adjusted our development of construction variations. Sänkiaho and Sillanpää [32] concentrated on the retention of pollutants in different construction layers across different seasons in a field of lysimeters. They used a mixture of sand and soil in a 1:1 ratio for growing media that was one of several layers at a 195 cm construction depth. The result of this study stressed, among other things, the role of vegetation if construction layers included fines, as the vegetation seemed to improve infiltration.

Bioretention is also studied in Finland at the field scale for snow piling and melting area [40] and street side [41,42]. The total construction depths in these experiments were 100 and 125 cm. However, the qualities of the growing media were not the focus of these studies, although construction included vegetation.

In this study, an alternative construction depth was brought to the test field (Figure 3). The total depth affects construction costs, the volume of materials, and their required transportation to and from a site. On the other hand, too shallow a construction would be impeded by frost that would complicate the infiltration during winter and springtime melting. In fact, the construction depth affects the use of materials, construction practices, and hydraulic functions during the cold season, and possibly vegetation growth.

The development of construction details in this study followed Hsieh [20] who proposed single media structures. This construction combined the growing media and filter layers, and had several advantages both practically and for maintenance. For landscape construction, several thin layers are difficult to create with an excavator and difficult to control for project management. The two variations in this study followed the idea of single filter construction. Under the single filter media, a transition layer was used instead of a geotextile, as fines have been found to clog geotextiles. In practice, replacing a clogged geotextile is not difficult, but would disturb vegetation and even require regular replanting. For that reason, geotextiles were not used in this experiment (Figure 3).

The drainage and transition layer materials used a grain size commonly available in Finland. However, the growing media in the single filter layer had to be developed and mixed from different sources. For growing media recommendations, there are two different main paths, as presented in Figure 2. It was not clear which path to use for the Finnish application as studies in cold climate have followed both paths. The experiments already completed in Finland aimed to control quality, and the vegetation or growing media was not the main concern. To this end, two different growing media were identified and used in the test field. The specifications for the growing media are described in Figure 4. A local soil supplier mixed the sandy growing media (growing media A) to follow the path of engineered sandy soil presented in Figure 2. This specification is repeatable and commercially available, but based on sandy soils that are either or are becoming rare near the growth centers in Finland. The organic matter originated from a non-commercial pile of composted tree bark that included earthworms. Typically, organic matter originates from peatlands in Finland, but in this study, peat was not used due to its controversial nature and uncertain future of regulation. The proportion of organic matter was measured and growing media A included 2.2% of organic matter by mass.

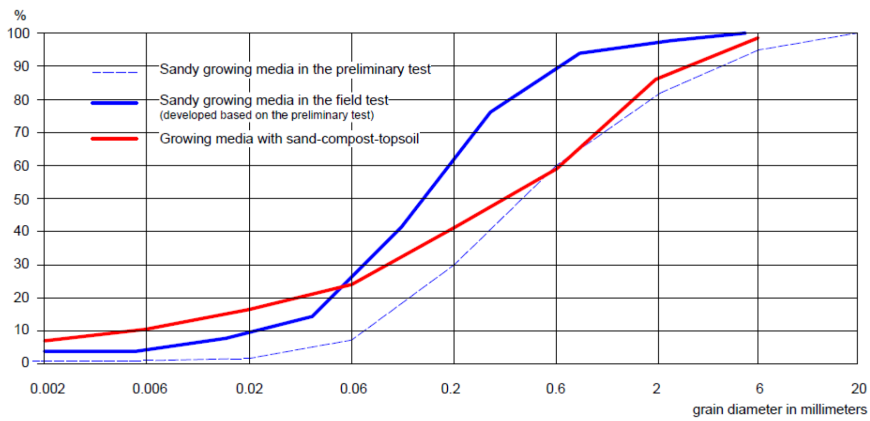


Figure 4. The grain size distribution of the growing media. Growing media A included 2.2% and growing media B included 5.3% organic matter by mass.

The other mixture (growing media B) was mixed at the site from local components. The mixture was created by the volume of earthwork buckets following typical on-site construction practices. The final mixture included, by volume, one-quarter sand #0–8, one-quarter fine sand #0–0.6, one-quarter leaf compost, and one-quarter topsoil from a nearby agricultural field. The proportion of fine sand was added to the final mixture, as the local sand #0–8 is meant for construction purposes and is low in fines. The leaf compost was well composted, but included some bigger tree pieces and plastic trash that were removed before installation. To collect the topsoil, the topmost surface of the site was peeled, but the proportion of topsoil still included weed roots along with earthworms. This final sand-compost-topsoil mixture included 5.3% organic matter by mass. The difference between the grain sizes of the growing media is shown in Figure 4. The figure also includes the distribution in grain size from another local study that used the same approach for sandy growing media. That study determined that the soil they used was too low in fine particles for vegetation growth [43].

Numerous possibilities exist for arranging the plant combination for bioretention. In this study, various plant species were not monitored separately, but rather in the form of a plant community. In order to keep the research design clear, the same plant combination was planted on all cells with growing media. Two criteria were created for the plant selection. First, the combination had to have structural diversity with several canopy layers. This criterion enabled the use of the bioretention as an element in urban design to form spaces, edges, and barriers (Table 1). Second, the combination had to be created from a variety of species to provide species diversity. The plant selection was based on a study that tested the tolerance of some plant species for short interval flooding [43], and from that study *Alnus glutinosa*, *Betula pubescens*, *Lythrum salicaria*, *Picea mariana*, *Rhododendron canadense*, and *Salix purpurea* 'Gracilis' were used in this plant combination.

Table 1. Plant combination and role of plants in structural diversity.

Name	Type of Plant		
	Edging or Groundcover	**Medium Shrubs or Tall Herbs**	**Small Trees or Large Trees**
Alnus glutinosa			×
Betula pubescens			×
Chelone obliqua	×		
Geum rivale	×		
Hippohaë rhamnoides		×	×
Iris sibirica	×	×	
Lythrum salicaria	×	×	
Physocarpus opulifolius		×	×
Picea mariana		×	×
Rhododendron canadense	×		
Salix purpurea 'Gracilis'	×	×	
Sanguisorba officinalis		×	
Thalictrum aquilegifolium		×	

3.3. Test Field

The test field was located outdoors and received local weather conditions such as evapotranspiration, natural precipitation in local actual conditions, temperature, and infiltration. It included five separate cells with two different construction depths. This enables a research design with a control cell and two soil mixtures with two construction depths at 800 cm or 1200 cm. All the cells were located below the surface level to prevent atypical frost from the side. Each cell was isolated from the surrounding ground with a rubber layer to collect the infiltrated water. A drainage pipe collected the water at the bottom of every cell and channeled it to the measuring station. Measuring stations and their data services were provided by EHP Technique Ltd. (Oulu, Finland) Surface levelling around the cells prevented natural surface runoff into the cells, although runoff could be artificially organized through irrigation. In addition, the closest weather station of the Finnish Meteorological Institute was 100 m away from the test field. This meant that both the input and output of the water amount was continually measured in the experimental cells.

The bottom size of all cells was 2 m × 2 m. The surface size varied around 5 m × 5 m as the edge slopes followed a tilt of 1:1 and two different depths were used. The used edge slope followed local implementation practices. The ponding area covered the same area as the bottom of the cell, where the elevation of overflow allowed a ponding depth of 20 cm. All the cells had the same vegetation combination on the surface. The control cell was a sand filter without vegetation. The test field layout and the location of experimental cells are presented in Figure 5.

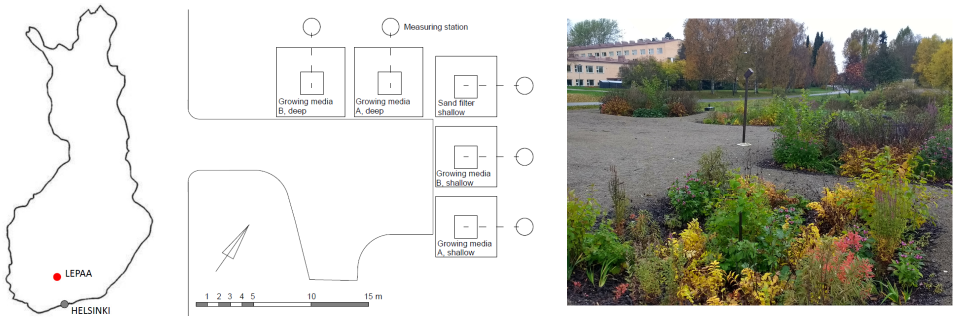


Figure 5. The test field located on the edge of agricultural fields at the Lepaa campus, Southern Finland. Sunlight and subsoil conditions were similar for all cells.

3.4. Test Field Experiments

3.4.1. Heavy Rain Simulations

The event-based hydrological functioning of the cells in the test field was measured during and after simulated heavy rain events that were executed by irrigation. This method allowed the study of the functioning of the constructions in extreme events as scheduled, to help expedite the research process.

All the cells received identical irrigation at the end of the first growing season. In this first year, the heavy rain simulations emulated 5.5 mm of heavy rain in 30 min, which may be repeated every second year. Here, we assumed that the runoff was collected from an impervious area of 227 m^2 that corresponded to 1250 L of irrigation for every cell. The assumed impervious area was approximately the same area of private garden roof areas and driveway or public parking areas in a residential area.

This irrigation procedure was repeated once a day for three days in two sequential weeks. During this time period, there was no precipitation; consequently, the irrigated water was the only water volume the cells received. The irrigated water volume was measured with a water meter and outflow ran continuously through the automatic measuring stations. Measuring stations saved the data of discharge (L/s), conductivity (μS/cm), and temperature (°C) every 10 min. The irrigation start time was recorded to study the delay between the water input and the beginning of the outflow in different cells.

In the first year, the irrigated water for the heavy rain simulations came from a nearby stream, and the electrical conductivity was measured before every irrigation session. The used water quality was not typical of storm water in urban areas. However, the change in electrical conductivity between the input and outflow provided a general overview on the quality management.

3.4.2. Functioning During Winter

The last heavy rain simulation took place at the beginning of October, and after that, the test field was not irrigated and was prepared for winter 2016–2017. During the winter period, the test field received only natural precipitation. The snow coverage and temperature data were provided by the Finnish Meteorological Institute and the frost depth data by the Finnish Environmental Institute. The frost depth data originated from the Pälkäne station (that is located 30 km north of the test field) and did not precisely describe the detailed situation in the cells. However, it described the general frost situation for the winter.

The automatic measuring station monitored the outflow of the cells during the whole wintertime and especially during the melting period. Water volumes were relatively low as only the natural rainfall stood on the cells.

3.4.3. Green Coverage

The plant material came from local nurseries in May 2016. All the root systems were washed and plants were replanted into the growing media used in the experiment. After replanting, the plants were grown in a greenhouse to ensure a functioning root system. Plants were planted into experimental cells at the beginning of June 2016.

The growth of vegetation was mapped and estimated by photographs and visual observation. The photos were imported to a CAD-based program and then scaled by the stakes defining the bottom area of the cells. Then, the green coverage of the cells was drawn, measured, and presented as a proportion of the total area. The green cover included all parts of growing vegetation in the bottom area of the cells, and was not separated by plant species. On that account, the monitoring concentrated on plant communities and their coping with different soil mixtures.

4. Results

These results concentrated on the monitoring and functioning of the cells after the construction phase; describing the initial performance of bioretention cells in the establishing phase. This timeframe excluded the possibility of discussing compaction, clogging, and change in hydraulic conductivity processes, as well as the long-term role of vegetation. However, these results compared construction depths and growing media in local conditions, their impact on bioretention retention capacity for event-based precipitation and wintertime functioning, and the change in the green coverage of the vegetation immediately after the construction phase.

4.1. Heavy Rain Simulations

The results of heavy rain simulations were based on six irrigation sets and the outflow patterns in a time series to evaluate lag time and volume reduction. The starting point of outflow after irrigation varied most between growing media B and the sand filter. The lag time in the sand filter was on average 22 min, whereas growing media A in a shallow cell was 70 min, and in a deep cell was 127 min. The lag time in growing media B was in a shallow cell was 30 min, and in a deep cell was 37 min. This delay corresponded with the cell's capacity to postpone the beginning of outflow as one component in a site scale storm water management.

The outflow pattern is presented in Figure 6. There, the shape of the outflow curve was different for the two types of growing media, and the depth of construction appeared to make no clear difference. The sand filter was the first cell to allow outflow, and the outflow continued rapidly so that 90% of the 20 h outflow volume was realized in less than four hours after the beginning of irrigation. The cells with growing media B roughly followed the same timeline allowing for 20 h outflow, but the total volume was 100 L lower and the beginning of the outflow was more gradual. The longest water holding was seen in both cells of growing media A. The cell with shallow growing media A allowed notable outflow after only two hours, and in the deep cell, after three hours. An apparent difference between the two types of growing media relied on the point in time when they allowed 90%, or even 70%, of the 20 h outflow volume (Figure 6).

Unexpectedly, growing media B showed better water holding capacity in the shallow cell than in the deep cell. However, the shape of these curves and the total water volume retained in cells was similar. Notably, these simulations occurred after the construction phase and at the end of the first growing season, and therefore the structures were not yet established.

The main differences between the cells were on the outflow curves in the first 8–10 h. Two hours after the beginning of irrigation, the cells with growing media A had not started to outflow, but the sand filter had outflowed 86% and the cells with growing media B had outflowed less than 70% of the 20 h outflow. Five hours after irrigation started, growing media B and the sand filter had already allowed more than 90% of the 20 h outflow, but growing media A was still in the early stage of the outflow pattern.

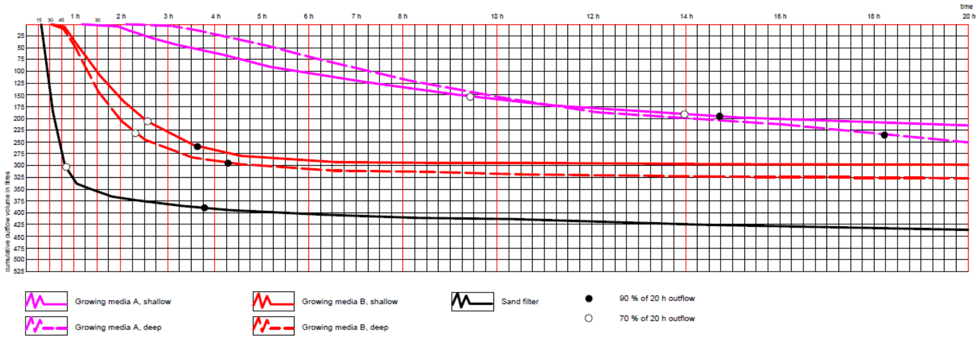
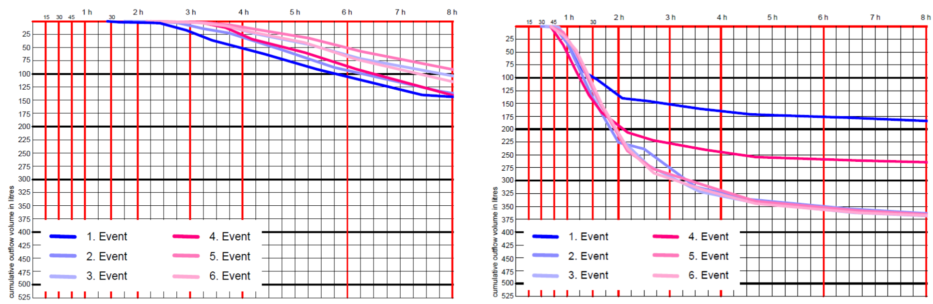


Figure 6. Cumulative outflow as a function of time, averaging six separate heavy rain simulations at the end of the first growing season. The irrigated water volume was 1250 L for every construction type.

Volume reduction was monitored for 20 h after the irrigations. Reduced outflow volume was measured from the bottom of the cells as no overflow existed. As the total volume of input water was 1250 L for every cell, the sand filter held 65%, the shallow growing media A held 83%, the deep growing media A held 78%, the shallow growing media B held 77%, and the deep growing media B held 74% of the water. The major outflow occurred during the first four to six hours for the sand filter and growing media B. However, growing media A allowed outflow still after 14.

The differences between the repeated single simulations within certain growing media showed a change in the outflow pattern in saturated and non-saturated conditions. Figure 7 presents the outflow patterns for eight hours after irrigation. The three first irrigations (blue lines) occurred on consecutive days and the second set of irrigations (red lines) occurred the next week. Between these irrigations, there was no precipitation. The first outflow curve showed a higher water holding capacity than the second and third. This demonstrated that growing media B allowed more outflow when its structure was saturated. However, this cell appeared to hold water relatively well in non-saturated conditions, even if the construction was completely saturated in the previous week. In contrast, the outflow curves of growing media A did not vary between single simulations.



(**a**) (**b**)

Figure 7. Outflow eight hours after separate heavy rain simulations: (**a**) deep growing media A shows similar outflow curves during all six events; whereas (**b**) the outflow curves of growing media B presented different patterns between the first events in the three-day series.

The effects of the type of growing media on the quality of the outflowing water were examined generally by electrical conductivity. These repeated irrigations demonstrated the media's capacity to retain nutrients. The electrical conductivity of the irrigated water varied between 121 and 125 µS/cm. Growing media A had low organic matter and nutrient content, and its discharge conductivity charge decreased after every irrigation (Figure 8). Notably, cells with growing media A were fertilized during the growing season due to the needs of the vegetation. Although the starting level of conductivity in growing media A was lower than in growing media B, the leaching seemed to be higher in growing media A. Growing media B had a more delayed and gentle change in conductivity rates after heavy rain simulations.

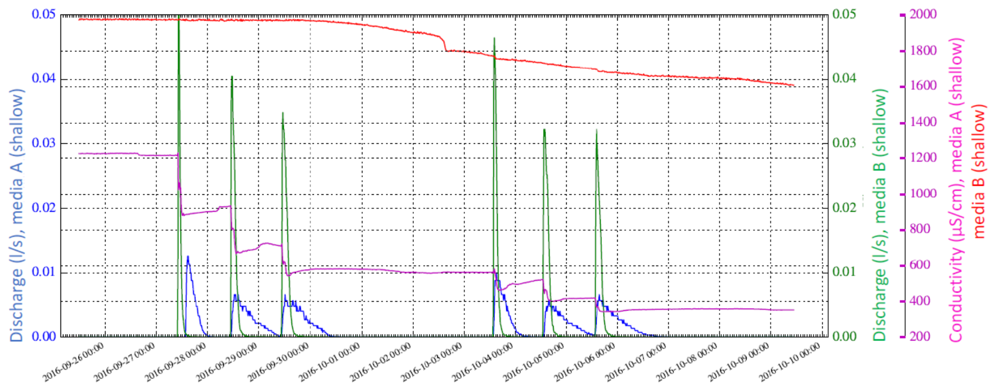


Figure 8. The change in electrical conductivity in the outflow quality during repeated rainfall events. The conductivity of the outflow in growing media A (purple) presented a steady decline after every heavy rain simulation, whereas the change in growing media B (red) was less clear, but followed a declining trend.

4.2. Functioning in Cold Conditions

Actual cold weather conditions in the test field provided a framework to monitor the cells' functioning during freezing and melting in the winter of 2016–2017. Compared to the average, this winter had an early start and a late end at the test field site. Table 2 shows that on average, there was less precipitation and temperatures were higher than in 1981–2010 [32].

Table 2. Monthly temperature and precipitation compared to averages in the test field area. Generally, the winter of 2016–2017 had less precipitation and more variable temperature conditions than the average.

Month	10	11	12	1	2	3	4	5
Temperature (°C)	3.7	−1.2	−1.6	−3.6	−4.5	0.3	1.8	9.1
Average 1981–2010	5	−0.3	−4.3	−6.2	−6.9	−2.6	3.5	10.1
Precipitation (mm)	13.6	42.2	15.6	13.9	20.6	23.5	46.3	16
Average 1981–2010	62	47	46	43	29	29	29	41

The last heavy rain simulation occurred at the beginning of October and after that, only natural precipitation reached the cells. Freezing conditions began at the beginning of November and the ground was covered with snow shortly afterwards. However, during the winter season there were two warm periods when the snow coverage melted before the freezing conditions continued. These two periods, in addition to the melting period in spring, provided the possibility to study the cells' outflow patterns after the construction phase.

The first melting period took place in mid-November when the frost depth reached a few centimeters. Outflow curves during that melting period showed that all the cells discharged to some extent. The second melting period happened in the second half of December, and the frost line at that time was more than 15 cm. This second melting period showed discharge activity mainly in the sand filter. However, this does not signify that the others were not active, but rather that there was no infiltrated water to discharge (Figure 9).

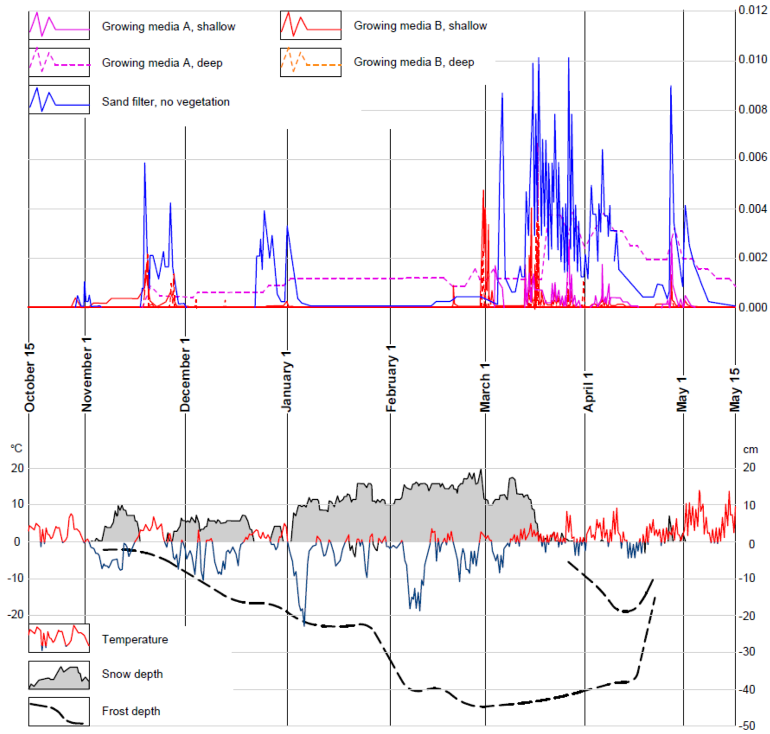


Figure 9. Functioning of cells in relation to weather conditions from mid-October to mid-May.

On average, the temperature rose to above zero in March and snow melted by mid-March. All the cells showed some levels of discharge before the snow melted even while frost remained in the ground. The sand filter showed the highest recharge during the winter. Growing media A had a high capacity to retain water in winter. The recharge pattern in growing media B was interesting as it appeared to have some outflow activity during the mid-winter melting periods and outflow was relatively early in spring when compared to growing media A.

4.3. Green Coverage

The development in vegetation cover showed notable differences between growing media A and B, even though cells with growing media A received additional fertilizers to maintain growth. All cells received good maintenance including weeding, pruning, and irrigation if needed, and these maintenance practices were similarly implemented across all cells. Growing medium A provided extremely weak growth at the beginning of the growing season, and had to be fertilized. After all, the difference between growing media A and B remained at the end of the first and at the end of the second growing season (Figure 10).

The construction depth only had a minor effect on vegetation cover, whereas the quality of growing media seemed to define the growth (Figure 11). Poor vegetation coverage in growing media A was compensated with fertilizers during the growing seasons to form the basis for a multilayered vegetation combination.

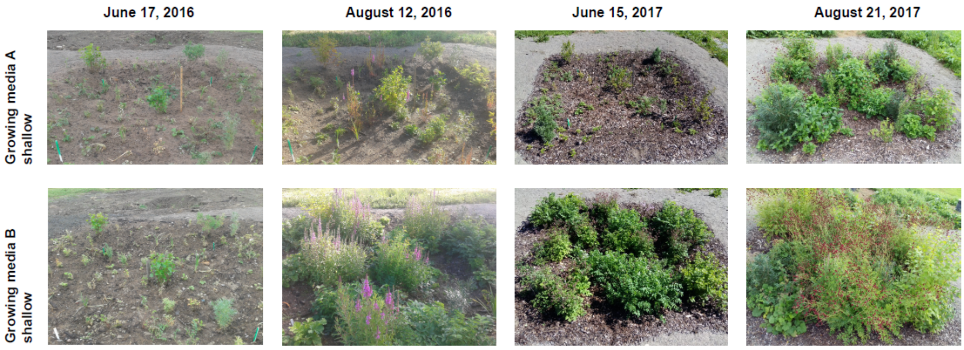


Figure 10. The development of vegetation cover in shallow cells with growing media A and B. The first photos were photographed one week after planting. Growing medium A showed light growth (upper row) when compared to the media containing compost and topsoil (lower row).

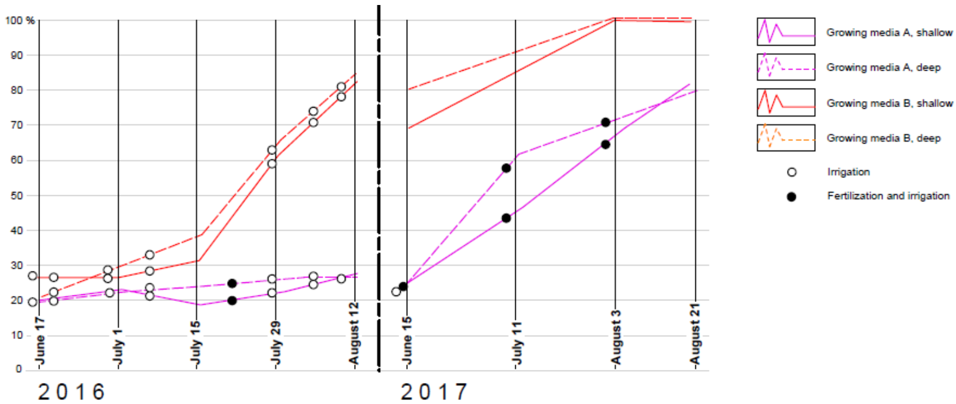


Figure 11. The development of green coverage and maintenance practices on vegetation mix.

5. Discussion

Urbanization and the growing proportion of impermeable surfaces increases urban run-off. Bioretention is one of the best management practices that can be used to address storm water management by combining water, soil, and vegetation. This integrative nature of bioretention is important in dense cities where the efficient use of space is important. However, the bioretention construction details can vary widely depending on different interests, disciplines, and locations. This study aimed to balance quantity, quality, and amenity when adapting bioretention construction to local practices. This knowledge addresses a contemporary interest in storm water management, especially for creating guidelines and instructions for Finland.

This study first outlined the bioretention schematic construction details based on local conditions, and then compared some possible lines of development in a test field on a mesocosm scale. The schematic construction used the idea of single filter media to keep the number of construction layers simple and to ensure good growing conditions for vegetation. The test field phase compared sandy and sand-compost-topsoil mixtures for growing media alongside two construction depths with a simple sand filter as a control. In this study, the comparison focused on the first year after construction and the first two growing seasons. Heavy rain simulations and observation on the change in green coverage demonstrated that the optimal solution for managing storm water was not optimal for vegetation.

The proportion of fines and organic matter in the growing media defines the construction's infiltration and water holding capacity. The content of fines in growing media A provided bioretention that prominently delayed peak-flow after rain events, but failed to support vegetation growth without fertilizers. This result supports the suspicions of Bratieres et al. [44] about the recommended filtration media without any added organic matter. Our study found it important to provide organic matter to fulfill the needs of the vegetation, which is important for bioretention systems that are designed to serve as an urban design element with a multi-layered canopy structure.

Heavy rain simulations compared cells under different precipitation conditions. A single irrigation simulating a heavy rain was followed with event-based monitoring, and a set of events showed the differences in repeated events. The main result of the heavy rain simulations showed the different water holding capacities and outflows in cells in the 20 h after irrigation. Growing medium A appeared to hold water the most efficiently before starting to recharge, and for the entire 20-h period. As Hsieh et al. [20] concluded, we demonstrated that hydraulic functioning can be different even when the media components were similar. Growing media B had better water holding capacity in the shallow cell than in the deep one. As this media was mixed on site in buckets of the excavator, it revealed the accuracy of practical implementation work.

However, vegetation growth was poor in growing media A in the first year, although these cells received extra maintenance to promote acceptable vegetation growth. If bioretention is considered as a multifunctional urban design element and not only for storm water management, the vegetation needs to be considered as an essential factor in the construction details. Here, growing media A failed to support good quality vegetation growth even with ongoing irrigation and fertilizers during the first year. The maintenance supporting the establishment of root system during the few first years may change the situation for upcoming growing seasons. This approach followed the idea of engineered and man-made biodiversity discussed by Levin and Mehring [11].

Although these results describe bioretention cells just after the construction phase, it needs to concentrate in future on the plant communities. Growing conditions may change thoroughly because of the growing media specifications, but also by runoff volume. This affects the survival of single plant species, and therefore direct planting design to use vegetation communities with several species rather than monocultural plantings. In particular, the idea of the dynamic planting concept may provide tools for bioretention as it builds on change (death and spread) in plantings, and therefore has potential to adapt changing conditions in bioretention cell.

Continuous monitoring of cells during the winter months in 2016–2017 indicated prominent activity during the melting periods during the winter, and during the spring melting. This observation indicated activity in the first winter, and should be further studied in upcoming years, together with frost type, and plant growth and mortality.

Our study demonstrated how construction details can be developed based on concrete local construction practices. The first-year functioning for storm water quality and quantity alongside the provision of a vegetative environment is essential in the context of rapid urbanization. However, the expected lifespan of a bioretention cell is 15 years and thus long term research is needed.

6. Conclusions

Construction details of bioretention should be modified to follow local construction practices and sustainable use of materials. However, it is essential to define first for what main purpose the adaptation serves: stormwater management, vegetation coverage or both. Growing media specifications, especially the content of fines and organic matter, is the choice that effects the vegetation growth. The specifications of growing media seem to concern designers and landscapers in detailed scale. Simultaneously this specification is the smallest component of the whole urban green network and storm water management.

Acknowledgments: This study was financially supported through Maiju and Yrjö Rikala's Garden Foundation and Helsinki Metropolitan Region Urban Research Program (KatuMetro).

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Jylhä, K.; Ruosteenoja, K.; Räisänen, J.; Fronzek, S. Ilmasto. In *Miten Väistämättömään Ilmastonmuutokseen Voidaan Varautua?—Yhteenveto Suomalaisesta Sopeutumistutkimuksesta eri Toimialoilla*; Ruuhela, R., Ed.; Ministry of Agriculture and Forestry: Tampere, Finland, 2012; pp. 16–23.
2. Novotny, V.; Ahern, J.; Brown, P. *Water Centric Sustainable Communities, Planning, Retrofitting, and Building the Next Urban Environment*; John Wiley & Sons: Hoboken, NJ, USA, 2010.
3. *RIL 261 Routasuojaus—Rakennukset ja Infrarakenteet*; Suomen Rakennusinsinöörien Liitto RIL ry: Helsinki, Finland, 2013.
4. Beatty, R.A.; Heckman, C.T. Survey of urban tree programs in the United States. *Urban Ecol.* **1981**, *5*, 81–102. [CrossRef]
5. Iakovoglou, V.; Thompson, J.; Burras, L.; Kipper, R. Factors related to tree growth across urban-rural gradients in the Midwest, USA. *Urban Ecosyst.* **2001**, *5*, 71–85. [CrossRef]
6. Keddy, P. *Wetland Ecology, Principles and Concervation*; Cambridge University Press: Cambridge, UK, 2010.
7. Dee, C. *Form and Fabric in Landscape Architecture: A Visual Introduction*; Spon Press: London, UK, 2001.
8. Echols, S.; Pennypacker, E. From Stormwater Management to Artful Rainwater Design. *Landsc. J.* **2008**, *27*, 268–290. [CrossRef]
9. Backhaus, A.; Fryd, O. The aesthetic performance of urban landscape-based stormwater management systems: A review of twenty projects in Northern Europe. *J. Landsc. Archit.* **2013**, *8*, 52–63. [CrossRef]
10. Davis, A.P.; Traver, R.G.; Hunt, W.F. Improving Urban Stormwater Quality: Applying Fundamental Principles. *J. Contemp. Water Res. Educ.* **2010**, *146*, 3–10. [CrossRef]
11. Levin, L.A.; Mehring, A.S. Optimization of bioretention systems through application of ecological theory. *Wiley Interdiscip. Rev.* **2015**, *2*, 259–270. [CrossRef]
12. Paus, K.H.; Braskerud, B.C. Suggestions for Designing and Constructing Bioretention Cells for a Nordic Climate forslag til dimensjonering og utforming av regnbed for nordiske forhold. *VATTEN J. Water Manag. Res.* **2014**, *70*, 139–150.
13. Lucas, W.C.; Greenway, M. A Study of Hydraulic dynamics in vegetated and non-vegetated bioretention mesocosms. In Proceedings of the International Conference on HydroScience and Engineering, Philadelphia, PA, USA, 10–13 September 2006.
14. Le Coustumer, S.; Fletcher, T.D.; Deletic, A.; Barraud, S.; Poelsma, P. The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Res.* **2012**, *46*, 6743–6752. [CrossRef] [PubMed]
15. Xu, S.; Liu, L.L.; Sayer, E.J. Variability of above-ground litter inputs alters soil physicochemical and biological processes: A meta-analysis of litterfall-manipulation experiments. *Biogeosciences* **2013**, *10*, 7423–7433. [CrossRef]
16. Liu, J.; Sample, D.; Bell, C.; Guan, Y. Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. *Water* **2014**, *6*, 1069–1099. [CrossRef]
17. Clar, M.; Laramore, E.; Ryan, H. Rethinking Bioretention Design Concepts. In Proceedings of the Second National Low Impact Development Conference, Wilmington, NC, USA, 12–14 March 2007; ASCE: Riston, VA, USA, 2007.
18. Carpenter, D.D. Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance. *J. Hydrol. Eng.* **2010**, *15*, 404–416. [CrossRef]
19. Somes, N.; Potter, M.; Crosby, J.; Pfitzner, M. Rain garden: Design, construction and maintenance recommendations based on a review of existing systems. In Proceedings of the Conference on Rainwater and Urban Design, Sydney, Australia, 21–23 August 2007.
20. Hsieh, C.; Davis, A.P. Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff. *J. Environ. Eng.* **2005**, *131*, 1521–1531. [CrossRef]
21. Ewing, C. *Assessment of International Bioretention Soil Media: Guidelines and Experiences*; University of Copenhagen: Copenhagen, Denmark, 2013.
22. FAWB. Guidelines for Filter Media in Biofiltration Systems (Version 3.01). 2009. Available online: http://www.monash.edu.au/fawb/products/obtain.html (accessed on 5 November 2017).

23. Kratky, H.; Li, Z.; Chen, Y.; Wang, C.; Li, X.; Yu, T. A critical literature review of bioretention research for stormwater management in cold climate and future research recommendations. *Front. Environ. Sci. Eng.* **2017**, *11*, 16. [CrossRef]
24. Muthanna, T.M. Bioretention as a Sustainable Stormwater Management Option in Cold Climates. Ph.D. Thesis, Norwegian University of Science and Technology, Trondheim, Norway, March 2007.
25. Khan, U.; Valeo, C.; Chu, A.; He, J. A Data Driven Approach to Bioretention Cell Performance: Prediction and Design. *Water* **2013**, *5*, 13–28. [CrossRef]
26. Moghadas, S.; Gustafsson, A.-M.; Viklander, P.; Marsalek, J.; Viklander, M. Laboratory study of infiltration into two frozen engineered (sandy) soils recommended for bioretention. *Hydrol. Process.* **2016**, *30*, 1251–1264. [CrossRef]
27. Blecken, G.-T.; Zinger, Y.; Deletic, A.; Fletcher, T.; Hedström, A.; Viklander, M. Laboratory study on stormwater biofiltration: Nutrient and sediment removal in cold temperatures. *J. Hydrol.* **2010**, *394*, 507–514. [CrossRef]
28. Khan, U.T.; Valeo, C.; Chu, A.; van Duin, B. Bioretention cell efficacy in cold climates: Part 1—Hydrologic performance. *Can. J. Civ. Eng.* **2012**, *39*, 1210–1221. [CrossRef]
29. Roseen, R.M.; Ballestero, T.P.; Houle, J.J.; Avellaneda, P.; Briggs, J.; Fowler, G.; Wildey, R. Seasonal Performance Variations for Storm-Water Management Systems in Cold Climate Conditions. *J. Environ. Eng.* **2009**, *135*, 128–137. [CrossRef]
30. Hunt, W.F.; Lord, W.G. *Urban Waterways: Bioretention Performance, Design, Construction, and Maintenance*; North Carolina Cooperative Extension Service: Raleigh, NC, USA, 2006.
31. Davis, A.P.; Hunt, W.F.; Traver, R.G.; Clar, M. Bioretention Technology: Overview of Current Practice and Future Needs. *J. Environ. Eng.* **2009**, *135*, 109–117. [CrossRef]
32. Sänkiaho, L.; Sillanpää, N. *Stormwater-Hankkeen Loppuraportti*; Aalto University: Espoo, Finland, 2012.
33. Pirinen, P.; Simola, H.; Aalto, J.; Kaukoranta, J.-P.; Karlsson, P.; Ruuhela, R. *Climatological Statistics of Finland 1981–2010*; Finnish Meteorological Institute: Helsinki, Finland, 2012.
34. Finnish Environmental Institute. Depth of Ground Frost. Available online: http://wwwi3.ymparisto.fi/i3/paasivu/ENG/Routa/Routa.htm (accessed on 16 October 2017).
35. Ruosteenoja, K.; Räisänen, J.; Venäläinen, A.; Kämäräinen, M.; Pirinen, P. Terminen kasvukausi lämpenevässä ilmastossa. *Terra* **2016**, *128*, 3–15.
36. Jylhä, K.; Ruosteenoja, K.; Räisänen, J.; Venäläinen, A.; Tuomenvirta, H.; Ruokolainen, L.; Saku, S.; Seitola, S. *The Changing Climate in Finland: Estimates for Adaptation Studies*; ACCLIM Project Report; Finnish Meteorological Institute: Helsinki, Finland, 2009.
37. Vainio, T. *Demand for New Dwelling Production in Finland 2015–2040*; VTT Technology 247; VTT Technical Research Centre of Finland: Espoo, Finland, 2016.
38. Ehrukainen, E.; Gustafsson, J.; Honkanen, M.; Härmä, P.; Jauhiainen, P.; Kuula, P.; Nenonen, K.; Pellinen, T.; Rintala, J.; Selonen, O.; et al. *Development of Aggregate and Natural Stone Industries in Finland*; Ministry of Employment and the Economy: Helsinki, Finland, 2015.
39. Väyrynen, T.; Aaltonen, R.; Haavikko, H. *Turvetuotannon Ympäristönsuojeluopas*; Pohjois-Pohjanmaan ympäristökeskus: Oulu, Finland, 2008.
40. Kasvio, P.; Ulvi, T.; Koskiaho, J.; Jormola, J. *Kosteikkojen ja Biosuodatusalueiden Toimivuus Hulevesien Käsittelyssä—Hule-Hankkeen Loppuraportti*; Finnish Environment Institute: Helsinki, Finland, 2016.
41. Suihko, M. Biofiltration for Stormwater Management in Finnish Climate. Master's Thesis, Aalto University, Espoo, Finland, 2016.
42. Lehikoinen, E. Kadun Vastavalmistuneiden Huleveden Biosuodatusalueiden Toimivuus Vantaalla. Master's Thesis, Aalto University, Espoo, Finland, 2015.
43. Tahvonen, O.; Riihimäki, M.-A. Urban Vegetation for Bioretention in Cold Climates—A Short Interval Flooding Test in Finland. In Proceedings of the ECLAS Conference 2016: Bridging the Gap, Rapperswil, Switzerland, 11–14 September 2016; pp. 497–500.
44. Bratieres, K.; Fletcher, T.D.; Deletic, A.; Zinger, Y. Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water Res.* **2008**, *42*, 3930–3940. [CrossRef] [PubMed]

Paper 6

Tahvonen, Outi. 2018. Scalable Green Infrastructure - the Case of Domestic Private Gardens in Vuores, Finland. Sustainability, 10, 4571.

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Scalable Green Infrastructure—The Case of Domestic Private Gardens in Vuores, Finland

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Received: 3 November 2018; Accepted: 30 November 2018; Published: 3 December 2018

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Abstract: The planning, implementation, and everyday use of the built environment interweave the green and grey components of urban fabric tightly together. Runoff from grey and impermeable surfaces causes stormwater that is managed in permeable surfaces that simultaneously act as habitats for vegetation. Green infrastructure (GI) is one of the concepts that is used to perceive, manage, and guide the components of urban green spaces. Furthermore, GI pays special attention to stormwater management and urban vegetation at several scales at the same time. This study concentrated on scalable GI in domestic private gardens. A set of garden designs in Vuores, Finland were analyzed and developed by Research by Design. The aim was to study how garden scale choices and designs can enhance GI at the block and neighbourhood scales to rethink design practices to better integrate water and vegetation throughout the scales. As a result, we propose a checklist for designers and urban planners that ensures vegetation-integrated stormwater management to enhance habitat diversity in block scale and possibility to use blocks of private plots for ecological networks. The prerequisite for garden designers is to be capable to balance between water, vegetation, and soil, and their processes and flows in detail the scale.

Keywords: garden design; scalable green infrastructure; systems thinking

1. Introduction

Ecosystem services support the well-being and health of urban residents. These benefits build up in a network of different kinds of urban green spaces that, together, can be considered an urban green infrastructure (GI). In other words, the urban fabric and its GI elements provide essential and nature-based benefits for residents as ecosystem services [1]. This approach includes a default definition of GI that comprises all shades of green in the urban context, including both public and private, and planned and unplanned urban vegetation, regardless of the land ownership or planned function. Therefore, GI and its shades of green penetrate all the land use categories.

However, the definition of GI is complex as the concept is applied to different purposes and scales. At its largest scale, the EU [2,3] perceives GI on a pan-European scale as a network joining the Natura 2000 areas that provide connections for fauna and appropriate patches for them to live in. At a smaller scale, detailed GI elements might concentrate on the techniques of green walls and roofs or best management practices in stormwater management [4]. Furthermore, discipline-specific definitions and uses make GI a multifaceted concept [5,6]. In the context of urban drainage management, GI is considered as networks of decentralized stormwater management practices, while landscape architects and urban ecologists use GI for describing networks of green spaces and landscape ecology [7]. According to Fletcher and others [5]: "A central tenet of green infrastructure is, of course, the use of vegetated systems to deliver desired ecosystem services". These approaches stress the connection of water and vegetation within GI.

While the definitions of the concept of GI depend on the used scale [8] and discipline [5], certain common attributes define its nature. GI is multifunctional, scalable, connective, and resilient [8,9]. Multifunctionality reflects the ecological, technical, and sociocultural functions that exist simultaneously in one space, such as buffering of climatic extremes, biomass productions, provision of habitats and biodiversity, species movement routes or opportunities for social interaction and nature experience. This division of multifunctionality to three main components, ecological, economic and sociocultural functions, relate the whole concept to sustainable development and its triple bottom line [10,11].

Urban planning deals with these attributes in all land use categories, including commercial, industrial, residential, and traffic areas, as opposed to just parks and conservation areas. While the share of the green component of the total surface of high-density areas is limited on its own, it can be integrated into buildings and constructions as well as green roofs and walls [12]. In addition, different land uses generate different concentrations of pollution in runoff, so considering multiple land uses simultaneously might complicate the design process [13]. From the perspective of GI, low density housing (LDH) is one of the most diverse land use categories. The GI of LDH comprises small areas managed by owners, and the needs and habits of gardens vary as time passes. These separate, small areas form a coherent gardenscape [14].

LDH and the garden matrix formed in the area cover a significant share of an urban area. According to Loram and others [15], the gardens of low density housing cover 22% of the surface area of examined towns and cities in the UK, while according to Mathieu and others [16], these constitute 36% of a town in New Zealand. The share of the gardens in LDH areas of total urban green spaces has been found to amount to 35–47% [15] or even over 50% [16]. It is assumed that the share of the garden area of LDH will continue to increase because of ongoing urbanization [17].

The characteristics of domestic gardens are determined based on plot sizes and the layout of buildings and parking spaces within the plot, as impervious surfaces prevent vegetation from growing. The ratio between impervious and pervious surfaces on a plot depends on the density, period of construction, and building types in the area [18]. The layout of this grey and impermeable proportion of a plot defines both the accumulation of stormwater and areas that may infiltrate and allow ground soil-based growth of vegetation. Furthermore, water and vegetation are interwoven through soil or growing media. The characteristics of soil determine both the hydraulic conductivity of water, the water storage, and the capillary action to bring water up the roots of vegetation, but also nutrient and water provision for the needs of vegetation [8]. Few studies have described the nature and extent of impermeable and permeable surfaces at a garden scale. Lawn is the most commonly used surface, covering 55–60% of the surface area [16,19]. The prevalence of pavement and asphalt has also been investigated, and a 13% increase was noted in their proportions in Leeds, UK over the previous 30 years [20].

Therefore, areas with LDH constitute a diverse gardenscape that serves as part of the urban ecological network and provides the same ecosystem services as other urban green spaces. It can therefore improve the air quality and microclimate as well as human health and wellbeing, contribute to stormwater management, and play a part in flood control [21].

This study examines how garden design can be used to improve the role of the gardens of low density housing as part of the GI and the effects of this on the block and neighbourhood scales. The main driver in this study is to explore the opportunities for developing GI from a perspective of garden design. The research data is based on the standard practices of the design process of the Research by Design method as well as choices made in an area with LDH in Finland. The research questions are as follows: How can garden designs that combine vegetation and stormwater management enhance GI at the garden scale? How is this improved design practice on the scale of plots reflected at the scales of the entire block and neighbourhood?

2. Theoretical Background: Planning and Design of Scalable Stormwater and Vegetation Systems

In the context of GI planning and design, scalability can be perceived at both the scales used in the design and the links between these as well as at a temporal scale. In the present paper, scalability primarily refers to spatial links between different scales.

2.1. Garden Scale

Plot-specific garden design brings together the needs of garden users and the conditions provided by a plot. In this context, the conditions consist of the layout formed by the placement of buildings in relation to the streets and the arrangements for entrances and car parking on the plot. This layout determines the need for passageways and, as a result, often also includes the extent and placement of impervious surfaces on the plot. In turn, the actual vegetation on the plot will be located in the areas that are free from impervious surfaces, although some vegetation may also be planted between the hard surfaces for purposes such as screening the yard from outsiders or improving the comfort of entryways.

From a garden design perspective, vegetation plays a number of different roles. While vegetation is one of the key elements for spatial design, it differs from other design elements, such as terrain shapes or structures, as it is living and changes constantly. In addition to creating spatial features, plants can serve as space dividers, frames to a view, or ornaments; produce biodiversity and a habitat for fauna as planting systems; and improve the microclimate; or provide screening to residential spaces. In addition to these goals, the selection of plants is determined by availability, factors related to growth potential at the design site, and hardiness [22,23].

Vegetation and water are the most fundamental and central elements of GI [8]. In the context of scalable GI, the smallest unit of vegetation is an individual plant, whose viability is based on the availability of water and nutrients at the growth site. If a growth site does not provide the conditions necessary for a plant to grow, these must be improved by means such as irrigation or fertilizing, or the plant's growth will be stunted or the plant may die [24]. However, the water centric approach to this small scale GI element concentrates on plants capability to minimize urban runoff. Ossola and others [25] studied how an increase in habitat complexity minimizes the urban runoff. They found three main factors: an increase in canopy density and volume, preservation of surface litter, and maintenance of the soil macropore structure. These factors apply to the plant scale.

When examining GI, particularly as a tool combining stormwater management and vegetation, two main approaches can be observed: vegetation integrated best management practices and tools stressing the extent of different surfaces. The Green Factor (GF) or similar tools give scores at the design stage to different surfaces and their proportions of designed area in order to improve the capacity of plots to generate urban green spaces. For example, the volume of growing media under a surface material can be a GF scoring criterion. While this is not a stormwater structure as such, it describes the water infiltration and retention potential under the surface materials [26,27]. However, stormwater management is more commonly based on sustainable urban drainage systems (SuDSs) that emulate the processes of the natural water cycle [28,29]. SuDSs provide a more or less standard toolbox of constructions with relatively well-known functions in order to manage the quantity or quality of stormwater. However, there are several approaches to categorize SuDS, and for instance Charlesworth and others [30] categorized SuDS into five device groupings (adapted in Figure 1). SuDS-based design has recently highlighted an aim of combining stormwater management with amenities and puts more emphasis on biodiversity [31]. This combines SuDS with urban vegetation. However, it is notable that not all SuDSs contain vegetation or rely on the processes of plant growth in stormwater management (Figure 1). This observation was supported by Wootton-Beard and others [32] as they claimed that urban design and planning require biology as well as engineering.

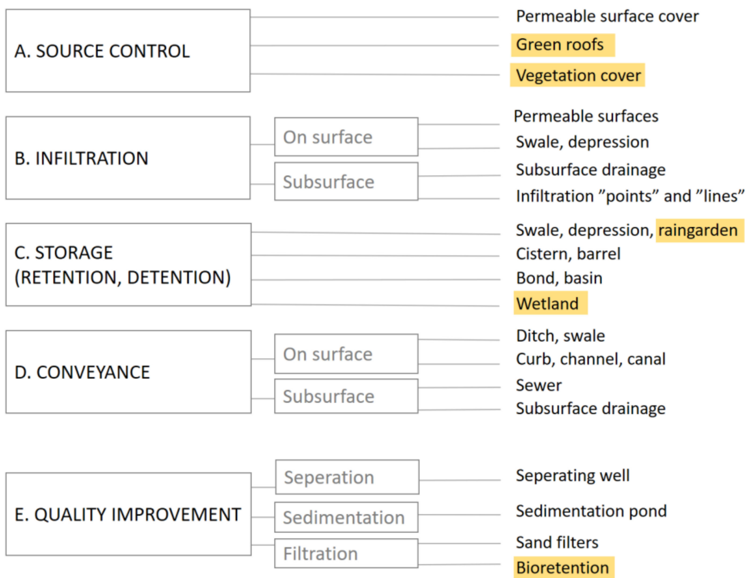


Figure 1. Sustainable urban drainage systems (SuDSs) devise grouping (in left) describes the general functions of stormwater management practices. These functions emulate the processes of the natural water cycle. Technical details of individual SuDS (in right) and their primary function define how they belong to different SuDS devise grouping. SuDS that contain pivotal and functional roles of vegetation are marked in yellow. (SuDS devise grouping adapted from [30], SuDS examples adapted from local practices described in [33]).

2.2. Scaling Up

In the water system, in contrast with separate SuDSs, stormwater management may also be designed as treatment trains. In these trains, a single SuDS is not assumed to solve the challenges concerning quantity, quality, or amenity, but instead, is perceived as an individual part of a larger solution [31]. Designing the trains also allows a better perspective of the different management practices in the whole design area to be obtained. As a result, the stormwater management of the upper parts of a watershed can be implemented with methods that reduce the volume of generated stormwater, while the approaches used at the lower parts of the system can be expected to level flood peaks and flows. However, the design of this treatment train must be viewed separately from flood passage design, as the treatment chain aims to solve the challenge of stormwater management in several consecutive sections. Therefore, an individual SuDS is not required to provide the most efficient solution possible, but rather, the tasks of stormwater management can be divided between the different parts of the treatment train.

Plot-scale treatment trains consist a set of SuDS placed in sequential order along the gradient. If it is not allowed to provide runoff or drained water from plots, then the treatment train consists only the SuDS inside the plot. However, the approach of treatment train applies also to up scaled water systems in blocks and neighbourhoods. At these scales the main focus is on different purposes and functions, or SuDS groupings according to Charleswoth [30], for the parts of the entire water management system.

When scaling up to watersheds or sub-watersheds, studies have been shown that the percentage of impervious surface area predicts the condition of the receiving water body [34]. With a higher proportion of impervious surfaces in the watershed, more problems are caused in receiving waterbodies by contaminants, erosion, and changes to temperature and flow rate [35]. Indeed, in urban planning, the Total Impervious Area (TIA) has been used as one of the indicators for the ecological impacts of planned construction and for estimation of pollutant loads from different land use categories [36]. Nonetheless, there are some weaknesses associated with the use of TIA in studies, which Brabec and others [34] have identified to include variation and a lack of clarity over which part of an impervious surface is directly connected to drainage system. As a result, the concept of the Effective Impervious Area (EIA) has been introduced alongside TIA. EIA only includes the impervious surfaces that are directly hydraulically connected to the drainage system. The concept does not include those impervious areas whose surface runoff is directed to areas covered with vegetation. However, the EIA has not been established as a standard indicator for planning and related steering, and the studies using the concept have mainly used it to describe existing neighbourhoods, focusing on plot-specific observations and aerial photographs [34,37].

In a plant system, the next scale up from an individual plant is a group of plants or a plant community. This may be a monocultural mass planting in a built environment or a habitat comprising various species in several overlapping layers. Recently multi-layer vegetation has been noted to be a key factor in supporting biodiversity [38,39].

The planning of urban ecological networks involves the identification of urban green spaces as patches, corridors, and matrices. Traditionally, the backbone for these networks has consisted of public green areas, such as parks, green spaces around streets, protective green zones, and conserved areas. In recent discussions, however, attention has been focused on the matrix between these patches and corridors, the exact part of GI that this study concerns [14]. When considering the urban green as a whole on a city scale, it is important to note that it plays a variety of roles in addition to the ecological one. These roles include curbing the urban heat island phenomenon, providing an environment for commuting and recreation, and fostering the equal availability of so-called green services to different residential areas [40].

3. Materials and Methods

This study explored the garden scale choices by first identifying a set of state-of-the-art garden designs and then developing and re-designing these garden designs to better serve GI by scaling them up to the block and neighbourhood scales. This development at the garden scale was carried out as an iterative design process during re-designing and upscaling.

The method followed the Research by Design (RbD) method, which explores practical design processes through several iterative and scientific reflective cycles [41], and systematically combines research inquiry and design thinking [42]. RbD, as one of the qualitative methods, aims not to gather numerical data, but focuses on the human element on how vegetation and stormwater management could be integrated during the design process in scales of gardens. According to Glanville [43], RbD combines both the research object and the means of carrying out the study. Here, the object was a set of garden designs that simultaneously serve as the means of carrying out the role of garden design in the context of GI in LDH.

This study applied the idea of grounded theory (GT) for analyzing the data produced in the design process of RbD. GT provides a general and non-discipline specific methodology that was used to analyze the iterative part of this study to reveal the conceptual context and linkages of vegetation-integrated stormwater management. Furthermore, GT allows a wide range of data collection methods.

On a city scale, urban green spaces, biodiversity, and green infrastructure are often studied by remote sensing or from satellite images that show the existing situation. In this study, garden designs were used to present a view of how things ought to be "instead of how things [actually] are" in accordance with Simon's [44] description of the difference between natural science and design.

3.1. The Context

The data of this study comprised 24 garden designs from the Vuores neighbourhood in Tampere, Finland, which served as the location for a national housing fair in 2013 (Figure 2). The gardens were designed and constructed simultaneously in the same area, and they followed the same design guidelines. The gardens can be considered to reflect the views of professional designers on the practical application of the main theme of the fair, sustainable stormwater management. The gardens in the fair area also play a significant role in creating an idea of a functional and ecological garden that meets today's standards among detached house constructors, as Finland's national housing fair is annually visited by nearly 100,000 people. According to surveys, visitors have reported getting ideas for their garden as one of the main reasons for visiting the fair [45].

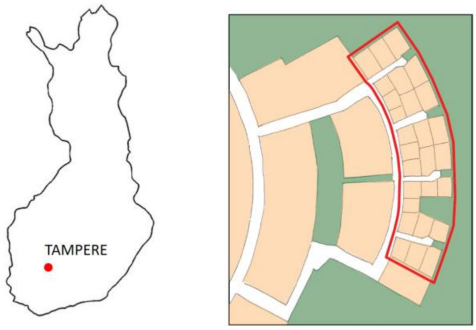


Figure 2. Vuores is a new development south of Tampere, Finland. This study concentrated on private domestic gardens and their garden designs in this area (marked in red). These plots are located between a large park/urban forest and multi-storey buildings.

3.2. The Process

This study examined designs and designing. The practical design work involved finding a balance between a number of factors (presented in Section 2.1), of which stormwater management or creating potential for biodiversity are only two examples.

First, the analysis of a set of existing garden designs concentrated on how the elements of stormwater management and vegetation existed and situated, and how they were integrated into the designs. Furthermore, the intended functions of these elements were mapped as it was the backbone of conventional design process. Then, in the second phase the garden designs were re-designed to improve water and vegetation integration, meanwhile the original layout and functions in plot scale were respected. These improved designs were further developed by considering their input first to block and then to neighbourhood scales. This scaling up and down provides an iterative design process that was repeated once for each plot. It was originally developed as garden scale designs, however, the outputs of these upper scales are also reported in this study (Figure 3).

In this study, RbD was used to provide several re-designing loops to ensure and develop designers approach to integrate vegetation with water. These loops were analyzed by coding and categorizing designs, that follows the applied methods in grounded theory (GT). Open coding was used to identify, name, and describe the development of designs. In coding we mapped all the main changes in the set of improved designs, meaning that the information in drawings was switched to written form. There were 2–8 coded changes or observations per design. These codes were then organized under categories describing more general themes, and they are presented in the section Vuores but also in the theory section. Our findings present inductively produced knowledge of designers' possibilities to integrate vegetation and water in plot scale. The theory concerning this finding is presented in the Section 2, but the core category, soil-vegetation-water system, is presented in Section 5.

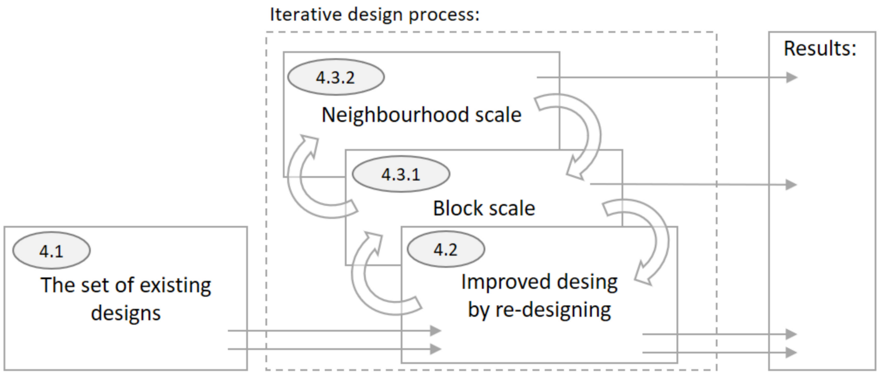


Figure 3. The used method, Research by Design (RbD), focused on the iterative process of re-designing the set of garden designs. This developed the garden scale designs by scaling up to the block and neighbourhood levels. The results of this study were based on the outcome of the garden scale development process, but findings are also presented on the block and neighbourhood scales. Numbers in the figure refer to section numbering in this paper.

The data included all available 24 garden designs in Vuores marked in red in Figure 2. This data seemed to be wide enough as the same categories started to appear in analysis and therefore the saturation of this data was achieved.

Although the research material was based on extremely practice-oriented work and its results, we consider this study to be an important addition to scientific research where the primary focus related to LDH has previously been on examining existing areas or investigating a single functional aspect. As noted by Harrison-Atlas and others [46], carefully defined studies that bridge the gap between science and practice are needed in the context of sustainability.

4. Results

Whether consisting of carefully prepared design documents or a series of separate choices made by an owner, the solutions related to the vegetation and stormwater management on a garden scale are defined in a garden design. In this section, we first analyze garden designs prepared by professional designers, and subsequently improve the integration of water and vegetation by re-designing these on plot, block, and neighbourhood scales.

4.1. Analysis of a Set of Existing Garden Designs

In garden design, decisions are made on the form and style of the overall layout, the location and sizing of different features, and the use of space dividers to separate different parts of the garden. The space may be divided into spaces using structures, planting areas, terrestrial elevation, or a variation in surface materials. While all of these elements were seen in the gardens in the Vuores housing fair site, the proportion of sealed surface was higher than in typical gardens. Paved pathways were used to support visitor movement during rainy days at the fair. In general, the design area was made for the everyday use of families. The Finnish housing fair concept did not adopt the show garden style with diverse and ornate plantings that is common in countries such as the United Kingdom.

Our analysis of the garden designs revealed, in this case, the difficulty of combining stormwater management with vegetation. In Vuores, plot sizes ranged between 454 and 935 m^2, and the floor area ratio was 0.35. These numbers depict the relatively high density of LDH in the Finnish developments. While opportunities for stormwater management have been provided in master planning, the garden scale solutions have primarily handled vegetation and stormwater management as distinct systems. For instance, gutters and water retention may even isolate vegetation from the SuDS. Moreover, narrow planting strips located in the middle of delineated paving may end up relying fully on irrigation water. At the time of the fair, stormwater management had only recently been introduced to the public discussion in Finland, and the main focus in the fair area was on presenting individual and, at times, rather isolated solutions and products. Stormwater management methods integrated in vegetation mostly consisted of rain gardens and the infiltration of small amounts of water at the edges of lawns [47].

In this set of designs, vegetation served five different main purposes. First, plants were used for property boundaries as both cut hedgerows and freely growing plant masses. Vegetation was also used as an element for separating the spaces and functions within the plot, in which case the elements usually consisted of shrubs or perennials. Some of the vegetation also appeared to serve an ornamental purpose. In some of the gardens, plants also contributed to food production in green houses and vegetable gardens, a task that relies on annual plants and their intensive growth during a single growing season. Lawns were the fifth use of vegetation; they were used to determine the shape of spaces, even if not otherwise demarcating the area. None of the garden designs retained the original vegetation of the plot. Figure 4a presents a schematic drawing of the types of vegetation and their locations and describes the overall arrangements of the gardens in the fair area.

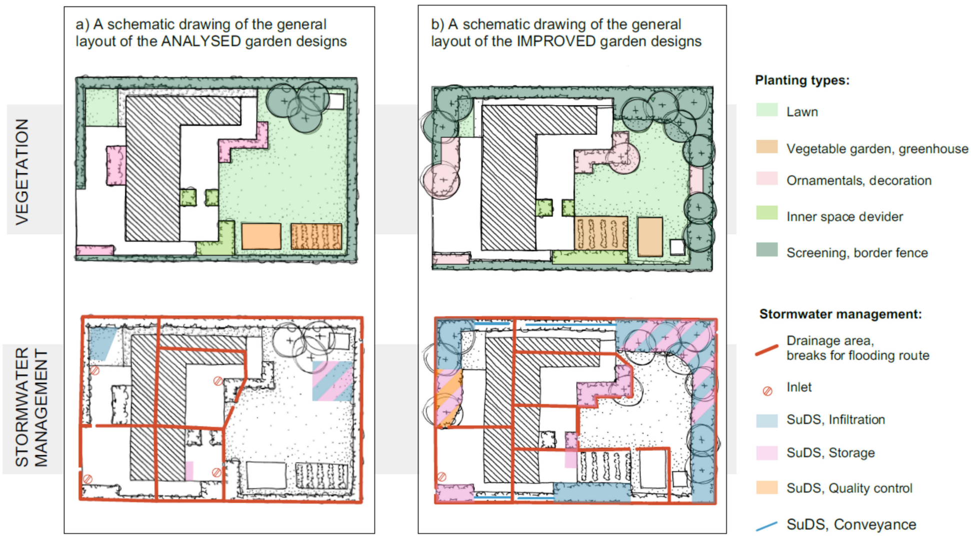


Figure 4. (**a**) A schematic drawing describing the arrangement of plotS, the volumes and locations of different planting types, and stormwater management; (**b**) The same schematic design after improving the integration of vegetation into stormwater management shows the change in vegetation's roles.

4.2. Improved Garden Designs

The following step included examining the opportunities for better integration of stormwater and vegetation when redesigning the gardens. The starting point was the general principles of the original design, and the aim was to retain the functions, styles, form, and space dividers used in the design (Figure 4b).

The first step in the design process was to refine the size of the planting areas according to their functional type. This led to enlarged planting areas which played a key role in property boundaries. Similarly, the inner space dividers located in the middle of the hardscapes were enlarged to better provide the required soil volume to improve both the infiltration capacity and the storage of water for the use of vegetation. Ornamental plantings also partly served as space dividers on the plots, especially when combined to raise beds or other constructions. For these, the utilisation of runoff must be more carefully considered as a raised planter may be totally separated from the soil by structures or capillary gaps. In practice, this first step means ensuring there is sufficient volume of growing media for water retention and plant growth.

The second step appeared to concentrate on the re-evaluation of the placement of the different planting types in relation to the runoff sources. Planting types with high water demand were located close to the downspouts and outer edges of impermeable surfaces to better benefit the available runoff. The designs revealed that ornamental plantings, in particular, if not growing in raised beds, and inner space dividers could benefit stormwater integrated growing conditions. For residents, these planting types are, in any case, part of the essential vegetation for gardening as a hobby. Of all planting types, greenhouses and vegetable gardens require the most water. Paradoxically, these types were usually placed at the most remote part of the plot, at the back of the yard, in the original designs. However, these plantings require a consistent supply of water to yield crops, and therefore, water storage in containers or barrels is needed.

The third step of the re-design process appeared to consist of defining a stormwater treatment train. The re-design process aimed to integrate the planting types and their water demands into the treatment trains. The single SuDSs in the original designs were transformed into multi-phase treatment trains. The aforementioned utilisation of the ornamental plantings or inner space dividers emerged as a central development. However, a challenge arose in this context due to the local recommendations which state that infiltration should occur at a distance of at least 3 m, and preferably 6 m from a building. Moreover, in Finland, ground frost sheets are used next to buildings at a 1.5-m distance from the wall base for ground frost insulation purposes, which sets limits for planting vegetation on the sides of buildings.

The re-design process revealed that the treatment train seems to form a linear set of separate SuDSs. This happens when designing starts solely with stormwater management. However, when designing is integrated with vegetation, it also expressly concerns extensive surfaces, such as large planting areas or entire lawns. In fact, the supply of water to these areas can be managed as extensive surface runoff that evenly crosses pavement borders. In an LDH plot, paved surface areas are primarily so small that no problematic erosion forms at the lawn borders. The situation may be different, however, if the water is initially directed to a certain point using kerbstones. A similar difference in approaches is also apparent in planning the management of water from a downspout (a spot-like release) or from paving used in the garden (as a wide front runoff). The utilisation of surfaces as part of the treatment train as water resources for vegetation was one of the key changes made to the original designs. This means that impervious surfaces should be perceived as water-generating areas and the vegetation surface should be perceived as an equal water-using area, even if it is not named as a method of SuDS. Therefore, all vegetation covered surfaces should be perceived as part of the stormwater management train, in which the slope and the material of the surface determine its effectiveness in stormwater management.

According to the examined garden designs, the placement of infiltrating SuDSs on the plots was based on, firstly, the avoidance of non-permitted infiltration areas and, secondly, the sizing of SuDSs. Moreover, in cold climates, snow, snow piling sites, and melted water on top of frozen ground require careful placement and sizing.

The practices of stormwater management including infiltration always require water flows to be perceived as both surface runoff and surface layer runoff. An examination of the water movement to the foundations of buildings and structures in relation to the drainage and frost insulation required revealed that any planting areas placed at the centres of paved areas must be carefully designed. This is due to the fact that sub-surface drainage systems intended to keep the base of a wall or pavement dry can easily be overburdened by the irrigation water used in an adjacent planting area. Another problem of subsurface drainage systems is that they are usually maintenance-intensive and prone to clogging issues [48]. Similarly, construction layers with big grain size cause the surrounding growing media to dry, in which case the volume of the growing media must be increased. In practice, this results in the planting areas in the middle of pavements and narrow stripes expanding.

As a whole, the integration of stormwater and vegetation in LDH plots appears to work well due to the relatively low water volumes. If a plot receives runoff outside its borders or if there is an uncommonly large impervious area, the potential for plot-specific stormwater management is naturally reduced. The design process that integrates vegetation with stormwater management needs to start with form and functions like any design process. Planting types are determined by the actual functions and spaces of a garden, and then plant water availability is ensured by appropriate runoff routes, infiltration, and storage. This vegetation integrated stormwater design creates treatment trains between different planting types and ensures that stormwater does not cause problems to constructions, garden use, or, if ponding occurs for a considerably long time, vegetation. It is of utmost importance to also include vegetated areas, such as mass plantings and lawns, instead of merely focusing on band-like substitutes for ditches.

4.3. Scaling Up

The plot scale designs were improved in stages. This gradual and iterative work progressed initially at the scale of blocks and subsequently, included the entire low density housing (LDH) area. This upscaling was used to examine the significance of plot-specific choices at higher scales.

4.3.1. Blocks

At the scale of blocks, even more emphasis is put on the placement of buildings and parking spaces than at the plot level. This is due to the fact that the building masses and their elevations form a block-specific micro watershed dividing front and back yards from each other. At the same time, this placement, combined with roof shapes, determines the volume of water accumulated from roofs to the part of the plot where the water must be managed. This also determines the amount of space available for stormwater management, and therefore also the set of suitable SuDSs.

At the block scale, re-designing revealed an opportunity for a so-called shared growing media volume which emerges at the borders of plots, as opposite planting areas are adjacent to each other. This is noteworthy, as growing media volume was one of the challenges observed at the plot scale. Utilising shared growing media volume naturally requires the planting areas to be located at the same section of the plot border, and there should also be no changes expected in the neighbours' plot use.

The block scale can also be used when working on large planting areas where plant communities (man-made habitats) can be developed. These habitats can emerge at the centres of blocks when water management and vegetation are located in the same area. In the blocks examined in this study, a stormwater flood route based on the locations of building masses and their elevations and a related vegetation area had already been created at the centre of the block at the planning stage. The design at the block level also included the use of this vegetation area for safe infiltration at a sufficient distance from buildings, and a possibility, to provide a harmonious forest stand and a resulting increase in crown closure on the block. This could allow the creation of larger vegetation-covered patches with multi-layer vegetation to support biodiversity on the block scale.

In addition to the slightly obvious definition for the multi-layer, eutrophic vegetation areas, this idea for habitat construction includes the examination of other built environment habitat types (Figure 5). Second, walkways and the sides of buildings, which are kept dry to ensure accessibility or healthy structures, create a dry growth environment on, and at the immediate vicinity of, these surfaces. As a result, the placement of buildings and walkways may form dry habitats across the borders of individual plots at the block level. At the same time, these areas between buildings tend to be the ones where inhabitants wish to use vegetation to create protective screening between plots and to the street. This produces third habitat type at the block level, where vegetation is planted on naturally dry spots in the middle of hard surfaces. The growth of sufficient media to retain water and nutrients must be ensured for this habitat type, and an adequate water supply must be provided for the planted vegetation. The fourth habitat type at the block level is comprised of vegetable patches that require regular moisture. While some plots may not include these, there are good grounds for placing these at the borders of plots adjacent to neighbours' patches to ensure the necessary humidity conditions and equal levels of light.

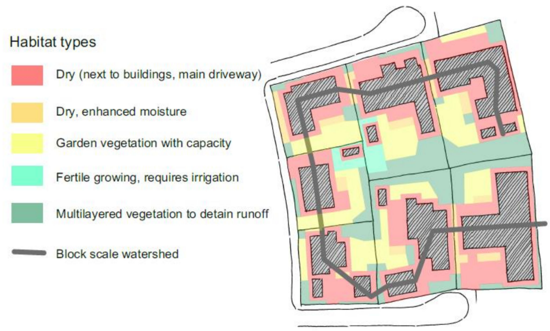


Figure 5. Adjacent plots formed five different habitat types for blocks. The moisture conditions in these habitats are based on the areas of construction layers and sub-surface drainage with irrigation dependent vegetation, with those with a high infiltration capacity with multi-layered vegetation in the centre of the block.

The fifth habitat type was open surfaces with low levels of vegetation—typically lawns and the planting areas commonly placed at lawn borders. At the block level, these lawnscapes are located in front of buildings and, particularly, next to patios. Even though lawns are rarely perceived as a part of stormwater management, the block-level examination revealed that they are located between water-producing hard surfaces and the eutrophic biotypes that need the most water, and they must therefore be perceived as part of the treatment trains.

4.3.2. Neighbourhoods

In addition to blocks consisting of plots, the GI of neighbourhoods comprises public parks and street networks. On the neighbourhood scale, vegetation is divided into trees planted alongside streets in a band-like formation or areas of plants around streets and vegetation patches in parks. Vegetation plays similar roles in parks as on the plots. However, in this area, vegetation is primarily perceived as forests and groves, meadows and other open spaces, or gardenesque sections of parks.

The layout of a neighbourhood divides the GI into the private green areas of blocks and the public green areas of parks and streets. Therefore, the layout of a neighbourhood defines what kind of GI continuum is created for people's physical activities and as a habitat for fauna. While urban planning is primarily concerned with the construction of the biophysical environment, functional connections, such as streams of water and nutrients, also affect the design of the GI, particularly at the neighbourhood scale.

Neighbourhood scale GI planning can utilise wooded patches growing in blocks as a kind of stepping stone passing through the area. This allows the lush parts of blocks to supplement broken ecological connections, support the landscape ecology patches located nearby, or create new connections. The shared growing media volumes of blocks may also be connected to park zones, thus providing possibilities for connections to the micro-organisms in the soil.

On this scale, watershed divides emerge as a result of the building masses in blocks and the elevations and inclinations of the street system. As such, street areas and kerbs serve as flood paths. However, water from the streets will primarily flow to the sewer system, as the ratio between pervious and impervious surfaces does not primarily favour SuDSs. The potential for urban green areas in stormwater management is determined by the scaling of the cross-section of the street area in urban planning. If the dimensions of streets allow it, a green street can provide a band-like connection through the street network in the form of trees planted alongside the street. On the streets along which plots are located, the stormwater management approaches are focused on water infiltration and increasing the delay in water flow (Figure 6).

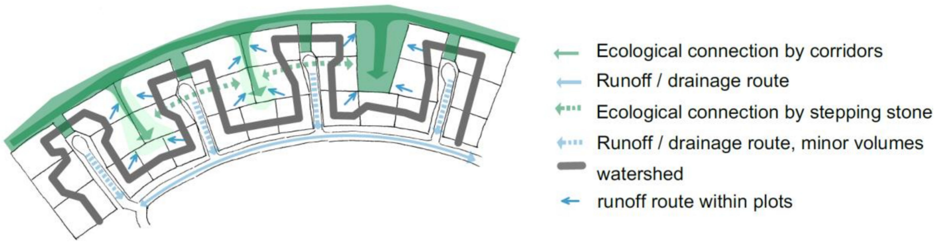


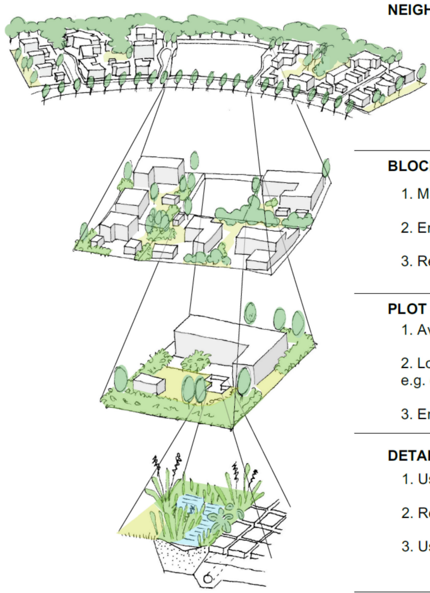
Figure 6. Neighbourhood scale defined flooding routes and vegetation patterns that may support the ecological network.

5. Discussion

The purpose of this study was to describe how the GI of an area with LDH can be developed by first, improving the garden scale designs to better integrate water and vegetation and second, scaling up from plot scale garden designs to habitats at the block scale and ecological networks at the neighbourhood scale. This bottom-up, decentralized approach follows Keeley's [49] claim about the need to develop the practices of GI planning. The results indicate that while combining stormwater management with the planting types typically used in garden design appears to work, this requires the recognition of their level of water demand. On the block scale, vegetation should make use of shared growing media between neighbours and rely the diversity of habitats that form from block scale arrangements of green and gray components. This block scale arrangement may form cohesive vegetation by shared soil volumes and smooth stormwater infiltration in the lowest corner. These habitats with multi-layer vegetation are determined in design at the scale of the entire neighbourhood, which includes the creation of a network of ecological corridors, patches, and matrices. Nonetheless, all types of habitats, from dry to water-absorbing plantings, should be appreciated in order to avoid inappropriate infiltration in areas that are drained with the means of constructions and their foundations.

Vegetation integrated stormwater management and, especially, the use of multi-layered vegetation, generates two simultaneous benefits. First, multi-layered vegetation provides a design element for defining a space and its edges. For this purpose, it is essential to have multi-layered vegetation. This space forming role of SuDSs is not too often discussed, and the guidelines seem to concentrate mainly on the nutrient removal capacity of vegetation, water tolerance, or presence of native species. Second, multi-layered vegetation has recently been mentioned in several studies as the key component of biodiversity [38,39,50]. Furthermore, this potential for biodiversity is proposed to especially rely on residential areas [39,51]. Figure 7 sums up our proposal for a designer's checklist to work with scalable GI that starts on plot scale designs.

Based on this study, there appears to be room for development in the design practices if the aim is to improve the GI of LDH. Vegetation integrated stormwater management requires constant assessment of the amount of water needed by vegetation and its capacity to tolerate ponding. However, this integration cannot be carried out without consideration of the surrounding environment and its moisture conditions in the foundations of constructions. Therefore, vegetation integrated stormwater management is based on stormwater management whereby treatment trains through vegetation-covered areas allow water to be infiltrated and stored in the growing media, thus allowing runoff be conducted slowly and as a wide front across planting areas and lawns in addition to other SuDSs. The main difference with this approach and traditional SuDS descriptions is that water is perceived as a resource that is necessary for plant growth and, additionally, the flows of water are perceived as surface layer runoff instead of only as surface runoff. This approach requires the understanding of both water and vegetation as well as the flows formed by the soil that conveys these.



NEIGHBORHOOD SCALE

1. Define the ecological network and watersystems
2. Define the role of private properties for areal systems
3. Ensure the defined role has space enough

BLOCK SCALE

1. Maximize the area of connected pervious areas
2. Enable the design of shared soil volumes next to borders
3. Respect also dry habitats next to buildings

PLOT SCALE

1. Avoid narrow band-like plantings especially in the middle of pavings
2. Locate multilayered and water demanding plantings close to sources, e.g. downspouts or impermeable surfaces
3. Ensure several steps to treatment train, use also large vegetated areas

DETAIL SCALE

1. Use SuDS including vegetation
2. Respect constructions, no infiltration to drainage
3. Use applied SuDS to provide growing conditions for multilayered vegetation

Figure 7. Proposed checklist for designers to work with scalable green infrastructure (GI) in low density housing.

In this system, soil is the interface between vegetation and water that enables water to filtrate, be retained, infiltrate, and rise due to capillary actions. In turn, vegetation absorbs the available water for its growth and releases water to the atmosphere. The decomposition of dead leaves and litter forms organic matter (OM) that contains nutrients needed for growth, and OM improves the water-holding capacity in soil that supports the availability of water to vegetation between rain events. OM supports the living conditions of micro-organisms, thereby improving biodiversity in the soil. In addition, the development of a root system supports water infiltration.

This core system of GI does not correspond to the traditional planting design process that includes the selection of plant species, but rather, is concerned with seeking a balance between soil, vegetation, and water. This system (a) can be found in some form on all surfaces of a built environment and (b) functions in constant interaction with the ways that people use areas and manage their gardens. Based on the results of this study, this system of water, vegetation and soil was identified to be a key factor in the design of vegetation integrated stormwater management. This finding is in line with the claims that the provision of ecosystem services builds on hydrologically active surfaces [52] and vegetated surfaces [53].

The proportion of sealed surfaces and their foundations limit the soil volume that is available for the system of water, vegetation, and soil. The smaller the space left for vegetation is, the more vulnerable the GI's CS is, and there might be a need to support this system by using fertilizers or irrigation. This brings up the question of what the minimum space for a self-sustaining GI core system is. If soil is considered solely as a filter through which stormwater infiltrates, the opportunity to provide soil water for vegetation is lost. The purpose is not to drown the plants with excessive water but to make sure that the soil holds available water for vegetation to withstand drought between rain events.

6. Conclusions

Garden scale GI can be enhanced by integrating stormwater management to vegetation, and this enhanced GI at plot scale affects also block and neighbourhood scales. This integration requires garden designers to have the knowledge of the interconnected system of water, vegetation, and soil and its on-going processes in the detail scale. This knowledge is essential when designing both good growing conditions for vegetation and technical safety for buildings and constructions. This integrative designing demands balancing between proportions of green and grey, impervious and pervious surfaces, to place the areas of water demand and runoff generation in relation to each other. Furthermore, designing must consider water flows not only on surface but also in surface layer next to construction foundations. This integrative approach needs to be the aim already in the early steps of design process. The careful design of separate vegetation or water systems will not suffice on its own.

Plot scale integration of stormwater and vegetation can provide improved growing conditions that serve for the continuum of different water demanding habitat types. Furthermore, it stresses the role of plots every square meter for stormwater management, not only the set of separate SuDS. This integrative approach starts from plot scale and the set of decisions in garden designs. However, urban planners need to realize its potential in block and neighbourhood scales as the outcome may improve biodiversity potential in the whole residential area and that returns back to residents as ecosystem services.

Funding: This study was financially supported through Maiju and Yrjö Rikala's Garden Foundation.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References and Notes

1. Davies, C.; Lafortezza, R. Urban green infrastructure in Europe: Is greenspace planning and policy compliant? *Land Use Policy* **2017**, *69*, 93–101. [CrossRef]
2. Supporting the Implementation of Green Infrastructure Final Report. 2016. Available online: http://ec.europa.eu/environment/nature/ecosystems/docs/green_infrastructures/GI%20Final%20Report.pdf (accessed on 1 December 2018).
3. Liquete, C.; Kleeschulte, S.; Dige, G.; Maes, J.; Grizzetti, B.; Olah, B.; Zulian, G. Mapping green infrastructure based on ecosystem services and ecological networks: A Pan-European case study. *Environ. Sci. Policy* **2015**, *54*, 268–280. [CrossRef]
4. Ahern, J. Green Infrastructure for cities. The spatial dimensions. In *Cities of the Future towards Integrated and Landscape Management*; Novotny, V., Ed.; IWA Publications: London, UK, 2007; pp. 267–283.
5. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.L.; et al. SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **2015**, *12*, 525–542. [CrossRef]
6. Wright, H. Understanding green infrastructure: The development of a contested concept in England. *Local Environ.* **2011**, *16*, 1003–1019. [CrossRef]
7. Benedict, M.A.; McMahon, E.T. Green Infrastructure: Smart conservation for the 21st century. *Renew. Resour. J.* **2002**, *20*, 12–17.
8. Pitman, S.D.; Daniels, C.B.; Ely, M.E. Green infrastructure as life support: Urban nature and climate change. *Trans. R. Soc. South Aust.* **2015**, *139*, 97–112. [CrossRef]
9. Kambites, C.; Owen, S. Renewed prospects for green infrastructure planning in the UK. *Plan. Pract. Res.* **2006**, *21*, 483–496. [CrossRef]
10. Mell, I.C. Green Infrstructure: Concepts and planning. *Forum eJ.* **2008**, *8*, 69–80.

11. Hansen, R.; Olafsson, A.S.; van der Jagt, A.P.N.; Rall, E.; Pauleit, S. Planning multifunctional green infrastructure for compact cities: What is the state of practice? *Ecol. Indic.* **2019**, *96*, 99–110. [CrossRef]
12. Koc, C.B.; Osmond, P.; Peters, A. A Green Infrastructure Typology Matrix to Support Urban Microclimate Studies. *Procedia Eng.* **2016**, *169*, 183–190. [CrossRef]
13. Tu, M.C.; Smith, P. Modeling Pollutant Buildup and Washoff Parameters for SWMM Based on Land Use in a Semiarid Urban Watershed. *Water Air Soil Pollut.* **2018**, *229*, 4. [CrossRef]
14. Tahvonen, O.; Airaksinen, M. Low-density housing in sustainable urban planning – Scaling down to private gardens by using the green infrastructure concept. *Land Use Policy* **2018**, *75*, 478–485. [CrossRef]
15. Loram, A.; Tratalos, J.; Warren, P.H.; Gaston, K.J. Urban domestic gardens (X): The extent & structure of the resource in five major cities. *Landsc. Ecol.* **2007**, *22*, 601–615.
16. Mathieu, R.; Freeman, C.; Aryal, J. Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery. *Landsc. Urban Plan.* **2007**, *81*, 179–192. [CrossRef]
17. Dewaelheyns, V.; Rogge, E.; Gulinck, H. Putting domestic gardens on the agenda using empirical spatial data: The case of Flanders. *Appl. Geogr.* **2014**, *50*, 132–143. [CrossRef]
18. Whitford, V.; Ennos, A.R.; Handley, J.F. City form and natural process indicators for the ecological performance of urban areas and their alpplication to merseyside, uk.pdf. *Landsc. Urban Plan.* **2001**, *57*, 91–103. [CrossRef]
19. Gaston, K.J.; Warren, P.H.; Thompson, K.; Smith, R.M. Urban domestic gardens (IV): The extent of the resource and its associated features. *Biodivers. Conserv.* **2005**, *14*, 3327–3349. [CrossRef]
20. Cameron, R.W.; Blanuša, T.; Taylor, J.E.; Salisbury, A.; Halstead, A.J.; Henricot, B.; Thompson, K. The domestic garden—Its contribution to urban green infrastructure. *Urban For. Urban Green.* **2012**, *11*, 129–137. [CrossRef]
21. Kelly, D.A. How Does Your Garden Flow? The Impact of Domestic Front Gardens on Urban Flooding. *Br. J. Environ. Clim. Chang.* **2016**, *6*, 149–158. [CrossRef]
22. Dee, C. *Form and Fabric in Landscape Architecture A Visual Introduction*; Spon Press: New York, NY, USA, 2001.
23. Booth, N.K.; Hiss, J.E. *Residential Landscape Architecture: Design Process for the Private Residence*, 6th ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2012.
24. Nouri, H.; Beecham, S.; Kazemi, F.; Hassanli, A.M. A review of ET measurement techniques for estimating the water requirements of urban landscape vegetation. *Urban Water J.* **2013**, *10*, 247–259. [CrossRef]
25. Ossola, A.; Hahs, A.K.; Nash, M.A.; Livesley, S.J. Habitat Complexity Enhances Comminution and Decomposition Processes in Urban Ecosystems. *Ecosystems* **2016**, *19*, 927–941. [CrossRef]
26. Keeley, M. The green area ratio: An urban site sustainability metric. *J. Environ. Plan. Manag.* **2011**, *54*, 937–958. [CrossRef]
27. Szulczewska, B.; Giedych, R.; Borowski, J.; Kuchcik, M.; Sikorski, P.; Mazurkiewicz, A.; Stańczyk, T. How much green is needed for a vital neighbourhood? In search for empirical evidence. *Land Use Policy* **2014**, *38*, 330–345. [CrossRef]
28. Kellagher, R. *The SUDS Manual*; CIRIA: London, UK, 2007.
29. "CIRIA SuDS Manual 2015".
30. Charlesworth, S.; Warwick, F.; Lashford, C. Decision-making and sustainable drainage: Design and scale. *Sustainability* **2016**, *8*, 782. [CrossRef]
31. Bastien, N.; Arthur, S.; Wallis, S.; Scholz, M. The best management of SuDS treatment trains: A holistic approach. *Water Sci. Technol.* **2010**, *61*, 263–272. [CrossRef]
32. Wootton-Beard, P.C.; Xing, Y.; Durai Prabhakaran, R.T.; Robson, P.; Bosch, M.; Thornton, J.M.; Ormondroyd, G.A.; Jones, P.; Donnison, I. Review: Improving the Impact of Plant Science on Urban Planning and Design. *Buildings* **2016**, *6*, 48. [CrossRef]
33. Eskola, R.; Tahvonen, O. *Hulevedet Rakennetussa Viherympäristössä*; Hämeen Ammattikorkeakoulu: Hämeenlinna, Finland, 2010.
34. Brabec, E.; Schulte, S.; Richards, P.L. Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. *J. Plan. Lit.* **2002**, *16*, 499–514. [CrossRef]
35. Arnold, C.L.; Gibbons, C.J. Impervious surface coverage: The emergence of a key environmental indicator. *J. Am. Plan. Assoc.* **1996**, *62*, 243–258. [CrossRef]
36. Kuusisto-Hjort, P.; Hjort, J. Land use impacts on trace metal concentrations of suburban stream sediments in the Helsinki region, Finland. *Sci. Total Environ.* **2013**, *456–457*, 222–230. [CrossRef]

37. Yang, B.; Li, S. Green Infrastructure Design for Stormwater Runoff and Water Quality: Empirical Evidence from Large Watershed-Scale Community Developments. *Water* **2013**, *5*, 2038–2057. [CrossRef]
38. Goddard, M.A.; Dougill, A.J.; Benton, T.G. Scaling up from gardens: Biodiversity conservation in urban environments. *Trends Ecol. Evol.* **2010**, *25*, 90–98. [CrossRef] [PubMed]
39. Threlfall, C.G.; Ossola, A.; Hahs, A.K.; Williams, N.S.G.; Wilson, L.; Livesley, S.J. Variation in Vegetation Structure and Composition across Urban Green Space Types. *Front. Ecol. Evol.* **2016**, *4*, 1–12. [CrossRef]
40. Fairbrass, A.; Jones, K.; McIntosh, A.; Yao, Z.; Malki-Epshtein, L.; Bell, S. *Green Infrastructure for London: A Review of the Evidence*; The Engineering Exchange: London, UK, 2018.
41. Roggema, R. Research by Design: Proposition for a Methodological Approach. *Urban Sci.* **2016**, *1*, 2. [CrossRef]
42. De Jong, T.; van der Voordt, T. Criteria for scientific study and design. In *Ways to Study and Research*; De Jong, T., van der Voordt, T., Eds.; Delft University Press: Delft, The Netherlands, 2002; pp. 19–30.
43. Glanville, R. Research Design and Designing Research. *Des. Issues* **1999**, *15*, 80–91. [CrossRef]
44. Simon, H.A. *The Sciences of the Artificial*; MIT Press: Cambridge, MA, USA, 1969.
45. Tahvonen, O. Impervious coverage in Finnish single-family house plots management and creating urban green spaces. *Archit. Res. Finl.* **2018**, *2*, 180–194.
46. Harrison-Atlas, D.; Theobald, D.M.; Goldstein, J.H. A systematic review of approaches to quantify hydrologic ecosystem services to inform decision-making. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2016**, *12*, 160–171. [CrossRef]
47. Tahvonen, O. Water for Vegetation—Knowledge Base for an Integrated Approach to Sustainable Stormwatern Management in Site Scale. In In Proceedings of the Eclas 2014 Conference, Landscape: A Place for Cultivation, Porto, Portugal, 21–23 September 2014; pp. 331–333.
48. Tu, M.C.; Traver, R. Clogging impacts on distribution pipe delivery of street runoffto an infiltration bed. *Water* **2018**, *10*, 1045. [CrossRef]
49. Keeley, M. Green Roofs Incentives: Tried and True Techniques from Europe. In In Proceedings of the Second Annual Green Roof for Healthy Cities Conference, Portland, OR, USA, 2–4 June 2004.
50. Beninde, J.; Veith, M.; Hochkirch, A. Biodiversity in cities needs space: A meta-analysis of factors determining intra-urban biodiversity variation. *Ecol. Lett.* **2015**, *18*, 581–592. [CrossRef] [PubMed]
51. Mumaw, L.; Bekessy, S. Wildlife gardening for collaborative public-private biodiversity conservation. *Australas. J. Environ. Manag.* **2017**, *24*, 242–260. [CrossRef]
52. Stone, B. *The City and the Coming Climate: Climate Change in the Places We Live*; University of Cambridge Press:: Cambridge, MA, USA, 2012.
53. Abunnasr, Y.F. Climate Change Adaptation: A Green Infrastructure Planning Framework for Resilient Urban Regions. Ph.D. Thesis, University of Massachusetts Amherst:, Amherst, MA, USA, 2013; pp. 1–243.

Aalto-DD 180/2019

Does the garden of a single-family house matter to the whole city? Private domestic gardens are multifunctional micro-oases that are carefully landscaped and constantly changed to reflect the preferences of their owners. Low-density housing characteristically comprises separate plots and their gardens, which are difficult to manage with the traditional tools of urban planning. However, this privately produced component of the urban green is part of the green infrastructure of the entire city.

The role of low-density housing in city-scale green infrastructure can be enhanced through integrative design of water and vegetation in garden-scale details and through the design process of gardens. This integrative design process requires a balanced understanding of the core system of water, vegetation, and soil, which forms the basis for green infrastructure that can be adapted for block, neighborhood, and city scales.

9 789526 087467

ISBN 978-952-60-8746-7 (printed)
ISBN 978-952-60-8747-4 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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