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Urban Green Infrastructure Planning: Multifunctional Networks for Sustainable Urban Development

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Dissertation

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“After 100 years of debate on how to plan the city, after repeated attempts – however mistaken or distorted – to put ideas into practice, we find we are almost back where we started. The theorists have swung sharply back to planning’s anarchist origins; the city itself is again seen as a place of decay, poverty, social malaise, civil unrest, and possibly even insurrection. That does not mean, of course, that we have made no progress at all: the city of the millennium is a vastly different, and by any reasonable measure a very much superior, place compared with the city of 1900. But it does mean that certain trends seem to reassert themselves; perhaps because, in truth, they never went away.”

(Peter Hall)

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List of Abbreviations

AMGI	Assessment of Multifunctional GI
CICES	Classification of International Classes of Ecosystem Services
DEM	Digital Elevation Model
DOP	Digital Orthophotos
DSM	Digital Surface Model
EC	European Commission
ES	Ecosystems
ESS	Ecosystem Services
GI	Green Infrastructure
GIS	Geographic Information System
LCA	Life Cycle Assessment
LULC	Land Use and Land Cover
MSPA	Morphological Spatial Pattern Analysis
NBS	Nature-Based Solutions
OBIA	Object-Based Image Analysis
RS	Remote Sensing
RSS	Regional Spatial Strategies
TEEB	The Economic Ecosystem Benefits
UFORE	Urban Forest Effects Model
UTM	Universal Transverse Mercator
UGI	Urban Green Infrastructure

Summary

The entire process of sustainable urban development is creative, changeable and challengeable. It requires new urban and landscape planning methods and government responses as well as management capacities to mitigate climate change, halt biodiversity loss and enhance ecosystem services. As an innovative planning and strategic method, urban green infrastructure planning aims to meet these challenges, in particular, by promoting multifunctionality and connectivity in green infrastructure. Nevertheless, the role of urban green infrastructure and the multiple ecosystem services provided by green infrastructure in urban areas is still marginal in urban planning processes. The lack of adequate mapping and functional analysis methods is a significant factor in this.

This dissertation, comprised of three papers, explores urban green infrastructure planning as an approach to enhancing multifunctional greenspace networks for sustainable urban development. It investigates the character of urban green infrastructure planning and fills research gaps by analyzing its multiple functions and undertaking connectivity mapping. Key research topics are the conceptual evolution of green infrastructure, the assessment of multifunctional green infrastructure as well as the spatial patterns in relation to equitable access for citizens to urban green spaces.

First, Paper I focuses on the conceptual development of green infrastructure and its respective functional analysis at various spatial scales. It examines what green infrastructure actually measures, and questions whether its current manifestations are consistent with its conceptual development. Furthermore, it seeks to find out whether there are specific trends in the conceptual evolution of definitions of green infrastructure, and whether there are gaps between this evolution and the implementation of green infrastructure in the context of advancing sustainable development. It demonstrates that at this point in time, multifunctionality is a core feature of green infrastructure and central to the evolving green infrastructure concept. Other important features or concepts related to green infrastructure are connectivity, sustainability, protection of biodiversity, urban focus as well as inter- and transdisciplinary collaboration. Paper I proposes ways of enhancing and applying the green infrastructure concept in the future, taking into consideration these key concepts. A key finding of Paper I is the lack of an integrative framework for the assessment of multifunctional green infrastructure.

In order to reduce this deficit, in Paper II, an integrated indicator framework is developed to evaluate the multiple ecosystem services provided by green infrastructure in urban areas. The second paper emphasizes that a clear framework and methodology are crucial for the sustainable management of spatially oriented green infrastructure plans over time and for different stakeholder groups. Hence, it proposes an explicit framework and methodology for the assessment of multifunctional green infrastructure, while addressing the pillars of urban sustainability (ecology, socio-economy, socio-culture and human health) and the multifunctionality of green infrastructure explicitly. For the purpose of validation, the integrative framework and methodology developed here are applied to an illustrative case study in Leipzig, Germany. This exemplification contains three stages of assessment: a conceptual framework for priority setting, a contextual assessment as well as a retrospective assessment. In total, 18 indicators are employed, and both hot and cold spots of selected green infrastructure functions and their multifunctionality are identified. Green infrastructure planners and policy makers may refer to this integrative indicator framework, which provides an application methodology as common grounds for better mutual understanding among scientists and stakeholders.

To advance the principles proposed in Paper I and answer the question of to what extent spatial patterns of urban green infrastructure may affect the spatial equity of access to urban green infrastructure for citizens, Paper III analyzes nine selected sample sites with regard to the connectivity of, and equitable access to, urban green infrastructure, representing three typical residential areas in the City of Leipzig, the fastest growing city in Germany. The third paper employs the morphological spatial pattern analysis approach (one finding of Paper I), exploring urban green infrastructure patterns in three typical residential districts in order to verify the similarities between the characteristics of spatial patterns in each residential type and to observe a tendency of decreasing equity from (semi-)detached houses to linear housing through to perimeter blocks. It depicts the spatial equity of green infrastructure distributions in typical residential areas from a morphological perspective, and thus further underpins urban green infrastructure planning for strategic networks as a key principle in the urban green infrastructure concept. The results pinpoint the necessity of developing further green infrastructure links in order to enhance structural connectivity as well as spatial equity. Overall, urbanization processes increase the need for urban green infrastructure to support the well-being of urban dwellers and to underpin a sustainable planning strategy. It is a challenge for urban planning to make cities socio-spatially equitable; it requires strategic planning based on measured gradients of spatial equity for green infrastructure. In conclusion, strategic urban green infrastructure planning should take into account the inherent spatial patterns and foster a fair distribution of green infrastructure towards spatial equity.

The integrative framework, methodology and results regarding the assessment of multifunctional green infrastructure and urban green infrastructure planning presented here contribute to discourses regarding the enhancement of the green infrastructure concept; they are expected to provoke further discussion on how to improve analytical methods for remote sensing data as well as how to exploit best remote-sensing-based methods at multiple spatial, temporal and spectral scales to support green infrastructure plans.

Keywords: green infrastructure, multifunctionality, connectivity, spatial equity, spatial patterns, urban planning, landscape ecology, urban green spaces

Zusammenfassung

Der Prozess nachhaltiger Stadtentwicklung ist kreativ, dynamisch und herausfordernd. Er erfordert neue Methoden der Stadt- und Landschaftsplanung genauso wie staatliches Handeln, verbunden mit einer größeren Kapazität für das Stadtmanagement, um die Auswirkungen des Klimawandels auf die Stadt abzuschwächen, den Verlust der biologischen Vielfalt aufzuhalten und Ökosystemleistungen zu verbessern. Als innovativer Ansatz der strategischen Planung zielt die urbane grüne Infrastrukturplanung auf die Bewältigung dieser Herausforderungen ab, insbesondere durch Entwicklung multifunktionaler und vernetzter grüner Infrastruktur. Dennoch ist die Rolle der städtischen grünen Infrastruktur und der vielfältigen Ökosystemdienstleistungen, die von grüner Infrastruktur in städtischen Gebieten erbracht werden, in Planungsprozessen immer noch marginal, da es an geeigneten Methoden zur Kartierung und Analyse ihrer Funktionen fehlt.

Die vorliegende Dissertation, die aus drei Artikeln besteht, untersucht die Planung städtischer grüner Infrastruktur als einen Ansatz zur Verbesserung multifunktionaler Netzwerke hin zu urbaner Nachhaltigkeit. Sie unterstreicht die Besonderheiten der Planung urbaner grüner Infrastruktur und schließt Lücken in der Analyse ihrer Funktionen und Konnektivität. Zentrale Forschungsthemen sind die konzeptionelle Entwicklung von grüner Infrastruktur, die Bewertung multifunktionaler grüner Infrastruktur sowie die Analyse der räumlichen Verteilungsmuster mit ihren Folgen für einen gerechten Zugang zu städtischer grüner Infrastruktur durch die Bevölkerung.

Zunächst konzentriert sich Aufsatz I auf die Entwicklung des Konzepts der grünen Infrastruktur sowie deren Funktionsanalyse auf verschiedenen räumlichen Skalen. Es wird untersucht, welche grüne Infrastruktur tatsächlich gemessen wird, und es wird hinterfragt, ob ihre aktuellen Erscheinungsformen mit der konzeptionellen Entwicklung konsistent sind. Darüber hinaus soll herausgefunden werden, ob es spezifische Trends in der konzeptionellen Entwicklung der Definitionen von grüner Infrastruktur gibt und ob Diskrepanzen zwischen dieser Entwicklung und der Umsetzung grüner Infrastruktur im Kontext der Förderung nachhaltiger Entwicklung existieren. Es wird gezeigt, dass zum gegenwärtigen Zeitpunkt Multifunktionalität ein Kernmerkmal von grüner Infrastruktur ist und im Mittelpunkt des sich entwickelnden grünen Infrastrukturkonzepts steht. Weitere wichtige Merkmale oder Konzepte im Zusammenhang mit grüner Infrastruktur sind Konnektivität, Nachhaltigkeit, Schutz der Biodiversität, städtischer Fokus sowie inter- und transdisziplinäre Zusammenarbeit. In Papier I werden Möglichkeiten vorgeschlagen, wie das Konzept der grünen Infrastruktur unter Berücksichtigung dieser Schlüsselkonzepte in Zukunft verbessert und angewendet werden kann.

Um den Mangel an einem integrativen Indikatoransatz zur Bewertung multifunktionaler grüner Infrastruktur zu schließen, wird in Aufsatz II ein integrierter Indikatoransatz entwickelt, der die vielfältigen Ökosystemleistungen grüner Infrastruktur in städtischen Gebieten bewertet. Der zweite Artikel zeigt, dass ein umfassender Ansatz und eine schlüssige Methodik für die Planung und das nachhaltige Management von grüner Infrastruktur unter Berücksichtigung räumlicher und zeitlicher Aspekte für verschiedene Interessengruppen entscheidend sind. Daher werden ein raumbezogener Ansatz und eine Methodik für die Bewertung multifunktionaler grüner Infrastruktur entwickelt, denen die Säulen der städtischen Nachhaltigkeit (Ökologie, Sozioökonomie, Soziokultur und menschliche Gesundheit) und die Multifunktionalität grüner Infrastruktur zugrundeliegen. Zum Zweck der Validierung werden der entwickelte integrative Ansatz und die Methodik auf eine beispielgebende Fallstudie in Leipzig, Deutschland, angewendet. Dieses Beispiel enthält drei Stufen der Bewertung:

einen konzeptionellen Ansatz zur Prioritätensetzung, eine kontextuelle sowie eine retrospektive Bewertung. Insgesamt werden 18 Indikatoren eingesetzt und sowohl Hot- als auch Cold-Spots ausgewählter grüner Infrastrukturfunktionen und deren Multifunktionalität identifiziert. Infrastrukturplaner*innen und politische Entscheidungsträger*innen können sich auf diesen integrativen Indikatorrahmen beziehen, der eine Anwendungsmethodik als Grundlage für ein besseres gegenseitiges Verständnis von Wissenschaftler*innen und Entscheidungsträger*innen bietet.

Um die in Aufsatz I vorgeschlagenen Prinzipien aufzugreifen und die Frage zu beantworten, inwieweit räumliche Muster städtischer grüner Infrastruktur die Zugangsgerechtigkeit für alle Bürger*innen zu städtischer grüner Infrastruktur beeinflussen können, analysiert Aufsatz III neun ausgewählte Beispielstandorte, die drei typische Wohngebiete in der Stadt Leipzig repräsentieren. Dazu werden die Konnektivität und der Aspekt eines gerechten Zugangs zu grüner Infrastruktur in Leipzig untersucht, da diese Stadt gegenwärtig die am schnellsten wachsende in Deutschland ist und deshalb unter hohem Nutzungsdruck steht. Der dritte Aufsatz verwendet den Ansatz der Morphologischen Raummusteranalyse (als ein Ergebnis von Aufsatz I), mit dem die Muster städtischer grüner Infrastruktur in diesen drei typischen Wohngebieten untersucht werden, um ihre Charakteristika und räumlichen Muster zu vergleichen. Die Ergebnisse zeigen eine Abnahme der Zugangsmöglichkeiten zu grüner Infrastruktur von der Einzelhausbebauung über lineare Geschosswohnsiedlungen hin zur Blockrandbebauung auf. Aufsatz III stellt die räumliche Verteilung der grünen Infrastruktur in diesen typischen Wohngebieten aus morphologischer Sicht dar und untermauert damit die Bedeutung der strategischen Entwicklung von grünen Netzwerken als ein Schlüsselprinzip des städtischen Grüninfrastrukturkonzeptes. Die Ergebnisse zeigen die Notwendigkeit auf, den Verbund von grüner Infrastruktur zu fördern, um ihre Erreichbarkeit zu verbessern. Insgesamt erhöhen Urbanisierungsprozesse den Bedarf an grüner Infrastruktur, die zum Wohlbefinden der Stadtbewohner*innen beiträgt und eine nachhaltige Stadtentwicklung befördert. Es ist eine Herausforderung für die Stadtplanung, Städte sozial-räumlich gerecht zu gestalten, wofür eine strategische Planung auf der Grundlage der räumlichen Bewertung des Zugangs zur grünen Infrastruktur erforderlich ist. Als Fazit ist festzuhalten, dass die strategische Planung der städtischen grünen Infrastruktur den inhärenten räumlichen Mustern Tribut zollt und einen gerechten Zugang zu grüner Infrastruktur im Sinne einer raumbezogenen Gerechtigkeit für alle Bürger*innen im Blick haben sollte.

Der vorgestellte integrative Rahmen, die Methoden und Ergebnisse zur Bewertung multifunktionaler grüner Infrastruktur und deren Planung tragen zum Diskurs über die Weiterentwicklung des grünen Infrastrukturkonzepts bei. Gleichwohl wird durch die Anwendung von fernerkundungsbasierten Methoden und Produkten auf mehreren räumlichen und zeitlichen Skalen eine verstärkte Nutzung dieser Datengrundlagen zur Unterstützung grüner Infrastrukturplanung sehr empfohlen.

Stichworte: grüne Infrastruktur, Multifunktionalität, Konnektivität, räumliche Gerechtigkeit, räumliche Muster, Stadtplanung, Landschaftsökologie, städtische Grünflächen

List of Publications

The following peer-reviewed scientific papers present the basis of this cumulative dissertation. At the time of the submission of this publication-based thesis, all of these papers have already been published in peer-reviewed journals.

They are referred to in the text in Roman numerals as follows:

I. **Wang, J.**, Banzhaf, E., 2018. Towards a Better Understanding of Green Infrastructure: A Critical Review. *Ecological Indicators*. 85, 758–772. https://doi.org/10.1016/j.ecolind.2017.09.018.

II. **Wang, J.**, Pauleit, S., Banzhaf, E., 2019. An Integrated Indicator Framework for the Assessment of Multifunctional Green Infrastructure — Exemplified in a European City. *Remote Sensing*, 11 (16), 1869. https://doi.org/10.3390/rs11161869

III. **Wang, J.**, Xu, C., Pauleit, S., Kindler, A., Banzhaf, E., 2019. Spatial Patterns of Urban Green Infrastructure for Equity: A Novel Exploration. *Journal of Cleaner Production*, 238, 117858. https://doi.org/10.1016/j.jclepro.2019.117858

Dissertation

This dissertation is based on the aforementioned three peer-reviewed papers. They are referred to in the text in Roman numerals and in bold throughout the entire thesis. At the time of submission, all of the papers have already been published in peer-reviewed journals. The author's contributions to each paper are stated in the following pages.

The peer-reviewed papers are summarized and discussed in the cross-cutting issues pertaining to the topic of this thesis (Chapter 2, 4, 5, and 6). They and their related appendix and supplementary materials are incorporated with the official and kind permission of the publishers (ELSEVIER & MDPI).

Paper I

Towards a Better Understanding of Green Infrastructure: A Critical Review
Wang, J., Banzhaf, E.
Published in *Ecological Indicators*. 85, 785-772. (Available online: 16 Dec 2017)
DOI: 10.1016/j.ecolind.2017.09.018

Summary

Based on a comprehensive analysis of key definitions of green infrastructure (GI) and their conceptual evolution, we present a review of current GI mapping approaches at multiple spatial scales and their associated functional analyses. GI is an approach that is used to combine ecosystem services and human well-being to realize an efficient and sustainable use of spaces; it is hereafter referred to as the "GI concept". The interdisciplinary database that forms the basis of our literature review includes peer-reviewed journal papers as well as books and documents published by international organizations, governmental agencies, and research institutions. By analyzing these publications – not only English but also Chinese articles – we present an exhaustive review that gauges the state and evolution of GI in chronological terms, and we discuss how GI should be further improved. We systematically examine what GI actually measures and question whether its current manifestations are consistent with its conceptual development. Furthermore, we seek to find out whether there are specific trends in the conceptual evolution of definitions of GI, and whether there are gaps between this evolution and the implementation of GI in the context of advancing sustainable development. We then draw attention to differentiation while analyzing GI functions and classifications. On this basis, we discuss six primary principles and propose a number of ways of enhancing and applying GI in the future. Our review shows that, at this point in time, special emphasis on the core idea of multifunctionality is significant in depicting the 'state of the art' of the evolving GI concept. Finally, the study identifies multifunctionality as the solution best suited to enhancing the GI concept and opening up potential avenues for further research.

Author's contribution

The first author J. Wang proposed the scrutiny of the concept, the data collection and the selection and evaluation of references, and developed the entire manuscript. J. Wang undertook the data analysis in this paper and evaluated the contribution to the GI concept made by each work of literature analyzed (both in English and Chinese). The co-author contributed to the manuscript by reviewing drafts and helping to enhance the discussion in the process of revision.

Paper II

An Integrated Indicator Framework for the Assessment of Multifunctional Green Infrastructure
— Exemplified in a European City.
Wang, J., Pauleit, S., and Banzhaf, E.
Published in *Remote Sensing*. 11(16), 1869. (Available online: 9 August 2019)
DOI: 10.3390/rs11161869

Summary

The aim of this study is on the one hand to provide an integrated indicator framework for the assessment of multifunctional green infrastructure (AMGI) in order to advance the evolution of the green infrastructure (GI) concept, and on the other hand to deliver an approach to conducting a GI assessment using remote sensing (RS) datasets at multiple spatial and spectral scales. Based on this framework, we propose an explicit methodology for AMGI, while addressing the multidimensional pillars (ecology, socio-economy, socio-culture, and human health) of urban sustainability and the multifunctionality of GI. For the purpose of validation, we present the extensive process of employing our framework and methodology, and provide an illustrative case study exemplified in a European city, i.e. Leipzig, Germany. In this exemplification, a single assessment is conducted in three stages: first a conceptual framework for priority setting, then a contextual assessment, and finally a retrospective assessment. In this illustrative case study, we include 18 indicators and identify hot and cold spots of selected GI functions and their multifunctionality. A clear framework and methodology are essential for the sustainable management of spatially oriented GI plans over time and for different stakeholder groups. GI planners and policy makers may therefore now refer to the integrative indicator framework and application methodology we have provided as common grounds for better mutual understanding among scientists and stakeholders. This study contributes to discourses on the enhancement of the GI concept and is expected to provoke further discussion on how to improve high-quality remote sensing data as well as how to enhance remote-sensing-based methods at multiple spatial, temporal and spectral scales to support GI plans.

Author's contribution

The first author J. Wang developed the entire manuscript under the supervision of S. Pauleit and E. Banzhaf. The data collection, data analysis and write-up were undertaken by J. Wang. In the process of rewriting and revision, the draft was thoroughly improved under the scientific instruction of S. Pauleit. All of the co-authors contributed to the manuscript by reviewing drafts and helping to enhance the entire paper in the process of revisions.

Paper III

Spatial Patterns of Urban Green Infrastructure for Equity: A Novel Exploration.
Wang, J., Xu, C., Pauleit, S., Kindler, A., Banzhaf, E.
Published in *Journal of Cleaner Production*. 238, 117858. (Available online: 6 Sep 2019)
DOI: 10.1016/j.jclepro.2019.117858

Summary

Urbanization processes spur the need for urban green infrastructure (GI) to support the well-being of urban dwellers and to underpin a sustainable planning strategy. It is a challenge for urban planning to make cities socio-spatially equitable; it requires strategic planning based on measured gradients of spatial equity for GI. Strategic urban GI planning should take into account the inherent spatial patterns and foster a fair distribution of GI towards spatial equity. Our aim is therefore to investigate the spatial patterns of urban GI and reveal how spatial patterns affect the spatial equity of GI in typical residential areas. The sample sites are in a central European city, Leipzig, the fastest growing city in Germany at present, with high pressure on urban growth. To elaborate an innovative approach, this study presents a cascade of three methodological stages: 1) deploy an urban morphological spatial pattern analysis (MSPA) approach in order to compare urban GI patterns in three typical residential local districts; 2) use the GI-adapted Gini coefficient to measure the spatial equity of GI distributions; and 3) explore the relationships between GI spatial patterns and the spatial equity of GI for each residential type. We combine MSPA with a spatial equity measurement in order to analyze three typical residential areas, i.e. (semi-)detached houses, linear multi-story housing estates, and perimeter blocks respectively. We are thereby able to prove that there are strong similarities between the characteristics of spatial patterns in each residential type and to observe a tendency of decreasing equity from (semi-)detached houses to linear housing and further to perimeter blocks. In terms of a significant finding pertaining to the support of strategic urban GI planning, we discovered that enlarging GI cores provides a limited increase in spatial equity; the increase is limited by a lack of space. Furthermore, we suggest more GI bridges to enhance structural connectivity as well as spatial equity. This paper depicts the spatial equity of GI distributions in typical residential areas from a morphological perspective, and thus further underpins urban GI planning for strategic networks as a key principle in the urban GI concept.

Author's contribution

The first author J. Wang developed this paper on the basis of intensive discussions with all of the co-authors; the discussions focused on the idea, the hypothesis and the research design in the context of the typical urban environments of Leipzig. The paper was further developed and fully improved with support from all the co-authors, especially the second author C. Xu. The data analysis sections and the design of the figures and tables were mainly undertaken by the first two authors, supervised and advised by all the other co-authors. The paper was revised by J. Wang. All co-authors contributed to the manuscript by reviewing drafts in the process of preparation, respectively (E. Banzhaf: three times, C. Xu.: once, A. Kindler: once, S. Pauleit: once, in the order of reviewing temporal sequence), and all of them greatly helped to enhance and improve the manuscript in the process of writing.

INTRODUCTION

“Look deep into nature, and then you will understand everything better.”

(Albert Einstein)

1 Introduction

1.1 Research background

Globally, 55% of the world's population was residing in urban areas in 2018 (United Nations, 2019). By 2050, more than 68% of the world's population is projected to be urban (ibid.). As urban areas continue to grow, the pressure to develop infrastructural solutions that are sustainable for humans and ecosystems is also increasing. Since the world is continuing to urbanize, strategic planning and management of urban growth is becoming increasingly important in sustainable urban development (Pauleit et al., 2019c). In the context of environmental pressures over the past few decades, green infrastructure (GI) has evolved from a novel buzzword into recognized planning strategies that have been used in various practices at multiple scales.

In recent decades, green infrastructure has been identified as one of several key strategies for achieving sustainability (Kopperoinen et al., 2014; Pauleit et al., 2019b; Tzoulas et al., 2007; Wang and Banzhaf, 2018). GI is regarded as beneficial because it can provide habitats for various biota, thereby protecting terrestrial and aquatic ecosystems (Demuzere et al., 2014; European Environment Agency (EEA), 2011; Ignatieva et al., 2011). Both GI and ecosystem services (ESS) have been widely promoted with the aim of improving environmental planning in relation to different spatial scales. The potential of GI and ESS is rooted in a holistic understanding of social, ecological and physical systems. GI was first introduced in the mid-1990s (Pauleit et al., 2011) and has since become part of the sustainability discourse used by a wide range of agencies, organizations, companies, community groups and planners. This concept offers practical ways of dealing with the rising rate of land consumption and fragmentation at various scales, while enhancing interdisciplinary collaboration and information sharing at different levels and offering the potential to achieve sustainable development and fair quality of life (Conservation Measures Partnership, 2004; EEA, 2015; Margules and Pressey, 2000; McDonald et al., 2005; Soule, 1991).

Rapid urbanization has motivated the development of urban GI as a planning strategy to support the well-being of urban dwellers (Coutts and Hahn, 2015; Tzoulas et al., 2007). Urban GI planning can be defined as "a strategic planning approach that aims at developing networks of green and blue spaces in urban areas that are designed and managed to deliver a wide range of ecosystem services" (European Commission (EC), 2012; Maes et al., 2019). That is to say, urban GI can mean the strategically managed networks of urban green spaces and natural and semi-natural ecosystems situated within the boundary of urban ecosystems (Maes et al., 2019; Maes et al., 2017). This thesis upholds this definition and assumes that planning for connectivity and multifunctionality in urban green and blue spaces are principles inherent in this definition (Hansen and Pauleit, 2014; Pauleit et al., 2018). Urban GI should strive to integrate green with gray infrastructures, e.g. for sustainable storm water management, and should be developed within a socially inclusive process that involves all relevant stakeholders. Among the multiple objectives of GI (European Commission, 2012) are the promotion of biodiversity, climate change adaptation, the provision of recreational spaces for citizens, and support for the transition towards a green economy (Pauleit et al., 2018).

Furthermore, urban GI planning should also strive to achieve relatively equal socio-ecological development (Pincetl and Gearin, 2013) by balancing disparities in the distribution of GI and its ecosystem services (ESS). The spatial equity of GI distributions is crucial in ensuring that individual urban inhabitants have the same degree of distance in terms of their access to services (Heckert and Rosan, 2016; Xu et al., 2018). The allocation of GI is influenced by the character of gray infrastructure, i.e. the amount, density and configuration of the built-up structures, roads and any other paved surfaces (Wang and Banzhaf, 2018). The spatial distribution and the character of different urban morphology types, such as residential areas and commercial and industrial zones (Gill et al., 2008; Pauleit and Duhme, 2000), therefore determine the quantity and quality of urban GI (Romero et al., 2012; van der Zanden et al., 2013). Consequently, urban GI planning will benefit from an analysis of the spatial patterns of GI, revealing the reciprocal relationships between GI and built-up structures (Pauleit and Duhme, 2000; Wickop et al., 1998). This means that studies focused on the spatial patterns of urban GI (Alberti and Marzluff, 2004; Holt et al., 2015), especially in residential areas, are useful for urban GI planning.

1.2 Research objectives

This dissertation project builds upon the existing theoretical foundations of urban ecology, green infrastructure, landscape planning and ecosystem services. It aims to strengthen the concept of green infrastructure as spatial planning strategies in urban areas.

The thesis is composed of **three research stages**:

Stage I: **GI concept analysis**: research on the concept of urban GI and other related concepts:

In this phase, there are three driving questions:

Q1 How has the concept of GI evolved over time, and which elements of that evolution are valuable in terms of further use?

Q2 What are the current GI mapping approaches, and how do they fit into the conceptual evolution of GI?

Q3 How can a combination of qualitative and quantitative information be used to better understand the multifunctionality of GI?

To answer these three questions in the conceptual development stage of this PhD project, the specific research objectives are as follows:

- To review and carefully scrutinize the state of the art of the conceptual evolution of GI and understand the ‘definition creep’ of GI as a concept.
- To review existing GI mapping approaches and tools in terms of different spatial scales and multiple functions of GI.
- To identify the most prominent aspects of GI which are capable of steering GI planning in a more efficient direction in the future.

Stage II: Establishment of a systematic framework for the Assessment of Multifunctional GI (AMGI) and **applying** it to the City of Leipzig, focused on significant aspects of the urban GI concept (extracted from Stage I). This is therefore the stage of framing a systematic methodology for the AMGI.

In this phase, the central research question is: How can a single AMGI be conducted using an indicator framework? To answer the central question, I came up with the following research objectives:

- To analyze indicator frameworks for AMGI in order to establish an integrated indicator framework that allows for the reflection of significant aspects of the urban GI concept.
- To develop an approach to undertaking AMGI using remote sensing (RS) and GIS-based methods.
- To deploy the proposed methodology in one European city, the City of Leipzig, Germany, and present the respective assessment results in all their strengths and weaknesses.

The potential benefit of this integrated indicator framework is that the concept of GI can be applied to various empirical analyses to optimize the planning of urban green spaces.

Stage III: An in-depth case study on urban GI as ecological networks, for the purpose of an in-depth exploration of spatial connectivity in GI.

As multifunctionality and connectivity are two major principles in reinforcing the GI concept and steering it in a more efficient direction (Pauleit et al., 2011; Wang and Banzhaf, 2018), I focus on spatial connectivity in the in-depth case study in Leipzig. This is the major purpose of the study in Stage III, because planning for connectivity and multifunctionality in urban green and blue spaces is a principle inherent in the conceptual definition of GI.

Therefore, in this phase, in order to undertake the case analysis on GI spatial connectivity, the underlying hypothesis is that the local districts with respective predominant residential structure types are subject to diverging morphological spatial patterns of GI, which may result in uneven GI equity.

The research objectives employed in verifying the aforementioned assumption are:

- To explore urban GI spatial patterns from the perspective of equity in typical residential areas.
- To compare urban GI morphological spatial patterns in different types of residential area in order to analyze the spatial equity of GI, using the GI-adapted Gini coefficient
- To investigate the relationships between GI's spatial patterns and the Gini coefficient in distinct residential types.

1.3 Staged research: Paper I to III

The scientific hypotheses and objectives introduced in Section 1.2 can be tested through these stages:

- ❖ **Stage I:** GI concept analysis
- ❖ **Stage II:** Establishment of the systematic framework for the Assessment of Multifunctional GI (AMGI)
- ❖ **Stage III:** An in-depth case study on urban GI as ecological networks, for the purpose of an in-depth exploration of spatial connectivity in GI.

The interactions and relationships between the three papers and how they are embedded into my doctoral project are illustrated in Figure 1.

I commenced my PhD project with a comprehensive literature review undertaken in **Paper I** in order to obtain an overview of the multiple scales and functions of GI and its mapping and planning in urban areas. Based on the findings of the literature review, the empirical studies conducted address two major issues within the GI concept – the assessment of multifunctional GI (**Paper II**) and the ecological connectivity of GI in urban areas (**Paper III**).

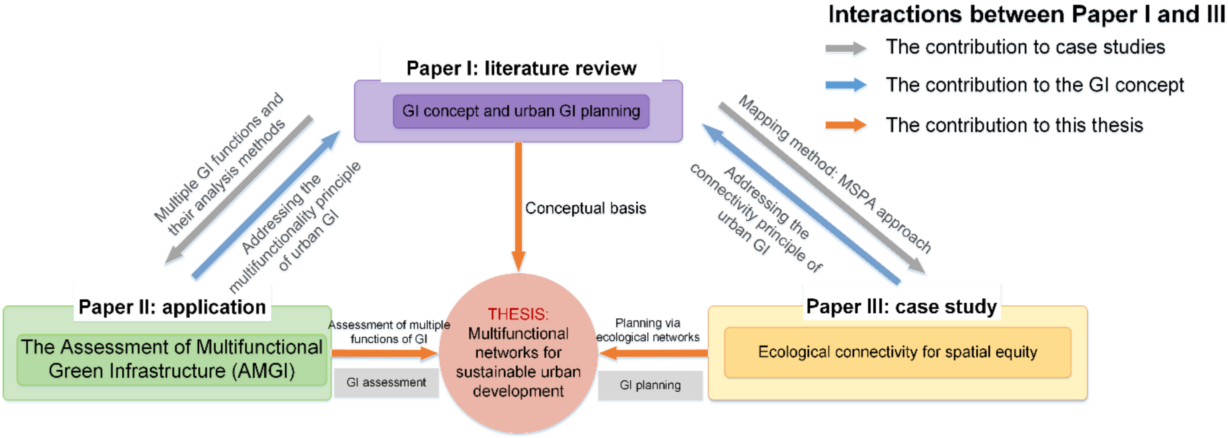


Figure 1. Relationships between the three papers and the dissertation (MSPA: morphological spatial pattern analysis)

Paper I concludes that most of case analyses in literature result in inevitable difficulties in GI assessment, because GI assessment depends on an integrative indicator framework for GI multiple functions extracted from benefit groups.

In **Paper II**, an integrated indicator-based framework for AMGI at urban scale provides a multidimensional and multi-scale indicator framework for the AMGI in general and exemplifies the methodology for conducting AMGI at urban scale in the City of Leipzig. The aim is to assess multifunctional GI through indicators and enhance the core idea of GI by addressing multiple dimensions of urban sustainability.

Paper III serves this dissertation through a connectivity focus. It contributes to the GI concept by addressing ecological connectivity for spatial equity. In this in-depth case study, GI spatial patterns are investigated using the morphological spatial pattern analysis approach.

In a nutshell, **Paper I** provides the framework for a GI functional analysis for **Paper II**, whilst its findings on the MSPA approach serve as the methodology for the empirical analysis of **Paper III.**

1.4 The structure of this thesis

Overall, the structure of this thesis is based on the conceptual development of GI (**Paper I**), selected frameworks for AMGI (**Paper II**) and the role of GI in spatial connectivity (**Paper III**).

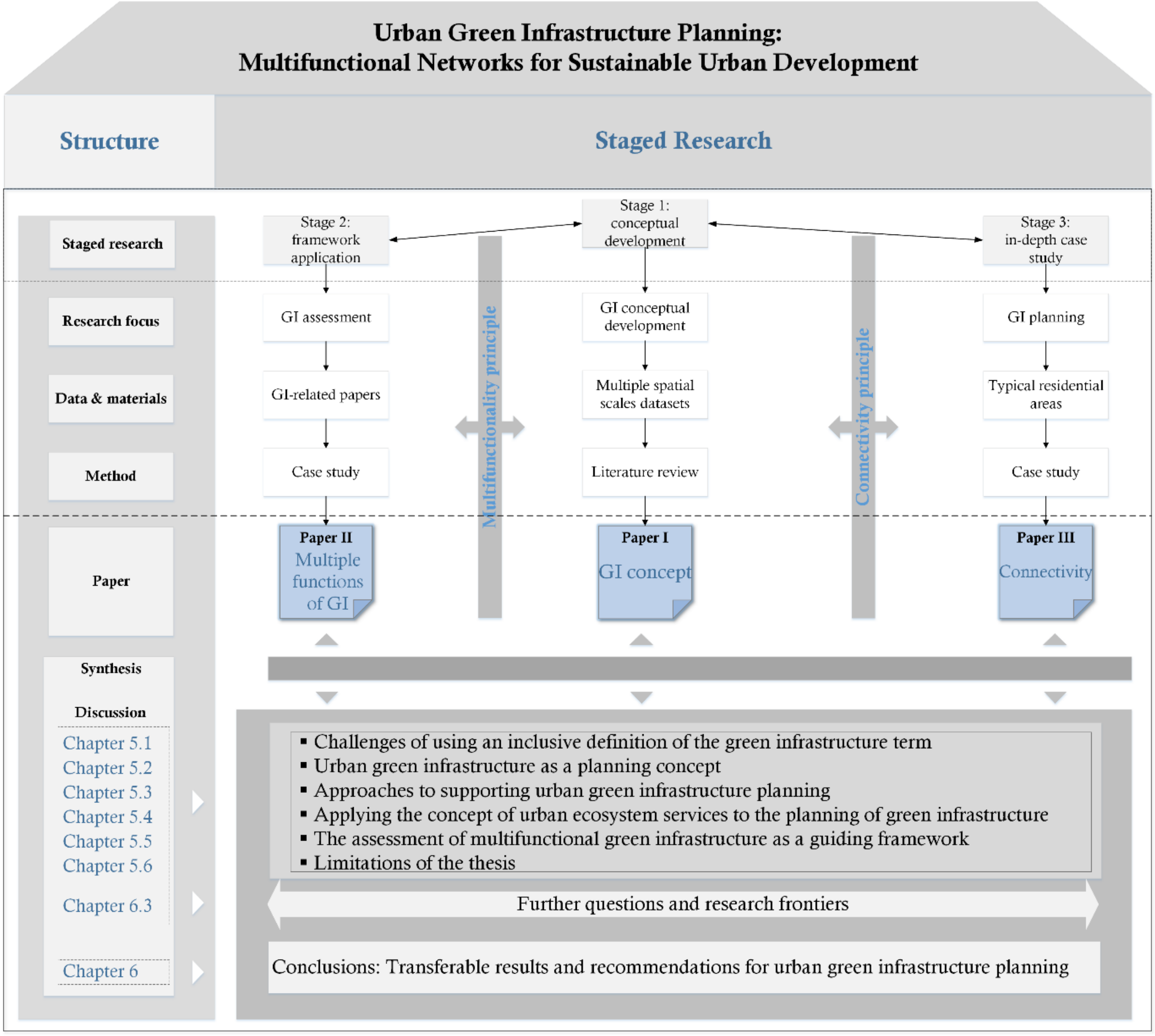


Figure 2. Structure of this thesis

The structure and organization of this thesis reflect the central questions and hypotheses underlying the project. Figure 2 provides an overview of the structure of the thesis and its embedded research projects. Reflecting the aforementioned hypotheses and scientific objectives, this thesis is structured around the research focus, materials, methods and results (in the left-hand box).

Paper I is the conceptual basis for the whole thesis. **Paper II** explores the multifunctionality principle and exploits the deployment of AMGI using the indicator-based method, whilst conveying the focus on multifunctionality in urban GI. **Paper III** is an in-depth study focusing on ecological connectivity. They therefore all contribute to the concept of GI and aim to strengthen the role of urban GI planning.

THEORETICAL FOUNDATIONS

“Real knowledge is to know the extent of one’s ignorance.”

(Confucius)

2 Theory and State-of-the-Art Concept

2.1 Theoretical background

2.1.1 Traditional planning

Urbanization is shaped by spatial and urban planning as well as by public and private investments in buildings and infrastructure (United Nations, 2019). Both the Green Paper on the Urban Environment (1990) and the fifth Environment Action Programme by the EU (1993-2000) have explained how spatial planning systems are key mechanisms in working towards sustainable development. Traditional planning and urban development have considered neither urban nor naturalistic open space as a system for structuring human settlement patterns (Austin, 2014). In traditional planning, open green space is not often employed in structuring the patterns of development. Instead, human settlements are often planned in accordance either with vehicular transportation routes or with transit-oriented development within high-density commercial and residential nodes (ibid.).

In the traditional planning paradigm, cities usually sacrifice social and environmental qualities where paved surfaces have been widely expanded and the building footprint is growing. Usually, the open-space elements and networks are not planned; they are more likely to form in a piecemeal way as parcels and lands are developed, rather than in a systematic way that optimizes space according to size, location, characteristics, multifunctionality and connectivity. This often results in the ecosystem and human values being separated into different dedicated spaces (Austin, 2014).

By way of a step forward, the European Commission (1997, p. 24) broadly defines spatial planning as approaches "used largely by the public sector to influence the future distribution of activities in space." Some spatial planning takes an "ecosystem approach", in which effective management of land and water provides a suite of ecosystem services for the benefit of humans and the natural environment (Wilkerson et al., 2018). Likewise, the expansion of GI in cities has emerged as a popular strategy for operationalizing this ecosystem-based approach to spatial land-use planning (Scott and Lennon, 2016). It has been widely accepted that sustainability requires a move to planning systems in which the urban ESS at local, regional and global levels are promoted as guidelines within which other considerations might be traded off (European Commission, 1996).

In this dissertation, I claim that the magnitude of the ESS provided to inhabitants can be increased and improved with the adoption of urban GI as a structural planning method. The physical activities, health and well-being of citizens in urbanized environments can be fostered through planning and physical design.

2.1.2 Urban green infrastructure as a strategic planning approach

The term GI was coined in 1994 as part of a planning that advocated for land conservation through a system of greenways. On the basis of a founded comprehension on the status of traditional and evolved urban planning, the whole doctoral project is constructed around a large number of new findings pertaining to urban ecology and planning. As one important achievement in urban planning, urban GI planning, in the GREEN SURGE project, is defined as follows:

> *"Strategic planning approach that aims at developing networks of green and blue spaces in urban areas designed and managed to deliver a wide range of ecosystem services. Urban GI planning aims at creating multifunctional networks at different spatial levels, likely from urban regional to city, and neighborhood planning. Due to its integrative, multifunctional approach, urban GI planning is capable of considering and contributing to a broad range of policy objectives related to urban green space such as conservation of biodiversity, adaption to climate change, and supporting the green economy." (Hansen, 2018; Hansen et al., 2016)*

This thesis is based on the idea that strategic planning and physical design in urban settings can foster various physical activities and the health and well-being of citizens in cities. Urban GI, such as planning for green streets, urban parks or allotments, has had a significant positive impact on urban inhabitants. The concept of ESS helps to grasp these influences in a structured manner. A common starting point for bringing ESS and GI together would be urban GI providing various ESS for citizens. As GI is usually discussed in conjunction with ESS, ESS frameworks such as CICES and TEEB provide a valuable taxonomy for classification (Haines-Young and Potschin, 2010; TEEB, 2010).

Significantly, GI planning is a strategic planning landscape approach to open space conservation, enabling local stakeholders such as communities, landowners and organizations to work together to identify, design and preserve the landscape network essentials for the maintenance of sustainable ecosystem services. It operates firstly at landscape scale, focusing on parcels and ownerships. Both GI and ecosystem services have been widely promoted as suitable strategies for improving environmental and urban planning at different spatial scales.

2.1.3 The development of urban green infrastructure planning globally

In Europe, urban GI planning at national and city levels has been strongly focused on the biodiversity aspect of ecological corridors, especially since the 1992 United Nations Convention on Biological Diversity (Austin, 2014). The concerns about biodiversity and natural conservation in the process of urban GI planning have been specifically addressed in the following planning at pan-European level: *Green Infrastructure – Enhancing Europe's Natural Capital* (European Commission, 2013), *Green infrastructure and territorial cohesion plans* (European Environment Agency (EEA), 2011), and the plans aim at enhancing the resilience of urban ecosystems through green infrastructure (Maes et al., 2019; Maes et al., 2017).

In the US, the first planned and implemented multifunctional corridor is the Emerald Necklace in Boston. It was designed by Frederick Law Olmsted in the 1880s and is a 455 hectare, seven-mile-long sequence of waterways and six parks. It focused on the connectivity of natural open space, recreation and flood control within the urban context of Boston. Some other cities in the US followed this plan and formed regional open space systems. Later on, the loss of open space and health considerations led to the re-creation of urban GI at national level. It was led by a *President's Commission on Americans Outdoors* by the Lyndon Johnson administration in 1987 (Maruani and Amit-Cohen, 2007; Wang and Banzhaf, 2018). The Commission's main proposal was a national network of corridors connecting residential districts to rural and natural landscapes within multiple functions such as greenways (the idea was given impetus by the book *Greenways for America* in 1990), the abandonment of railroad rights-of-way in favor of pedestrian and bicycle access, and wildlife corridors between habitat areas (President's Commission on Americans Outdoors (US), 1987).

GI planning in the UK builds on the legacy of ideas and initiatives going back over 150 years, e.g. city parks, garden cities, green belt, community forests (Liverpool City Coucil, 2010). Going back to the 1930s, the UK began designating greenbelts to restrain suburban expansion (Grant, 2010), and these currently account for 13% of the land area in the country (Austin, 2014). As one aspect of planning legislation in the UK, the *Planning Policy Guidance 2: Greenbelt* outlined land-use objectives and set out improperly developed greenbelts in 1995 and in later amendments in 2001. It was stated that these greenbelts should play a more positive role in providing access, opportunities for recreation, retaining and enhancing landscapes, improving damaged land, securing nature conservation and retaining land uses in primary industries. Different from the conventional land conservation and natural resource protection approaches, GI planning in the UK aims to form a bridge between land development, human-made infrastructure planning and the natural environment (Benedict and McMahon, 2006). It therefore seeks to optimize land use to meet the needs of human and nature – it is a mechanism for delivering sustainable development.

Against the background of a prosperous era for Asia in the 21st century (United Nations, 2019), GI planning for the environment in Asian countries such as Japan, Thailand, China and South Korea is incrementally increasing in diverse ways. A series of green plans has been developed in Japan, for example, in early 1939, Tokyo installed a comprehensive master plan of parks and open space at various scales across approximately 9,600 km^2 of the Greater Tokyo area (Yokohari et al., 2008). The enclosed GI developments ranged from urban parks, cemeteries and allotment gardens in the central district to areas of scenic beauty (Yokohari et al., 2008) and national parks in the remote mountains. Although this ambitious GI plan was poorly implemented, a few fluvial corridors were realized and remain as urban green landscape to date (Yokohari and Bolthouse, 2011; Yokohari et al., 2008). As for Bangkok, Thailand, there were several proposals for GI development plans for the green belts on the eastern and western outskirts of Bangkok in 1960 (Hara et al., 2008), which were located across a 25km radius with 700km^2 of rice paddies (Yokohari et al., 2008).

In China, the concept of urban GI was proposed in the guise of similar ideas, such as ecological infrastructure, ecological solutions and, more recently, the Sponge City concept. It has been integrated with the core idea of urban ecological security, aiming for a high-efficiency of ecosystem services. Building urban ecological security patterns has been a goal in several cities such as Beijing (Han et al., 2015), Shanghai (Su et al., 2011), Tianjing (Han et al., 2015) and Hangzhou (Wang and Li, 2009). There are two typical examples of ecological network design, as shown in Figure 3.

The very first GI 'seed' was sown in 1995 (Yu, 1995a), when Yu developed the concept of security patterns (SPs) (Yu, 1995a, b; Yu, 1996). These SPs were the starting point for GI mapping in China. This key strategy for GI approaches was adopted by his planning team at Peking University and Turenscape, and was applied in the context of Chinese urbanization, e.g. Taizhou city in 2005 (Yu et al., 2005), growth planning for Beijing based on ecological infrastructure in 2011 (Yu et al., 2011), and the urban river system of Liupanshui in 2014 (Yu & Turenscape, 2014). Yu's ideas comprise SPs actually conceived as GI for supporting abiotic, biotic and cultural functions (Ahern, 2007), thereby providing sustainable ESS. As an application of this GI approach, the National Ecological Security Pattern Plan (2008) included each individual ecological process analysis and evaluation based on individual ecological SPs – headwater conservation, storm water management, flood control, remediation of desertification, soil erosion prevention and biodiversity conservation (Yu, 2014). Generally, although Chinese urban green space system planning has played an important part in Chinese urban planning and has simultaneously been somewhat directive and workable over the past few years, there is still no 'rigorous' GI planning in China, neither at national level nor at city level (Wang and Banzhaf, 2018). Thus, the GI concept has great potential for Chinese urbanization plans such as the new-type urbanization plan (2014-2020) released on 16th March 2014 for environmentally friendly cities.

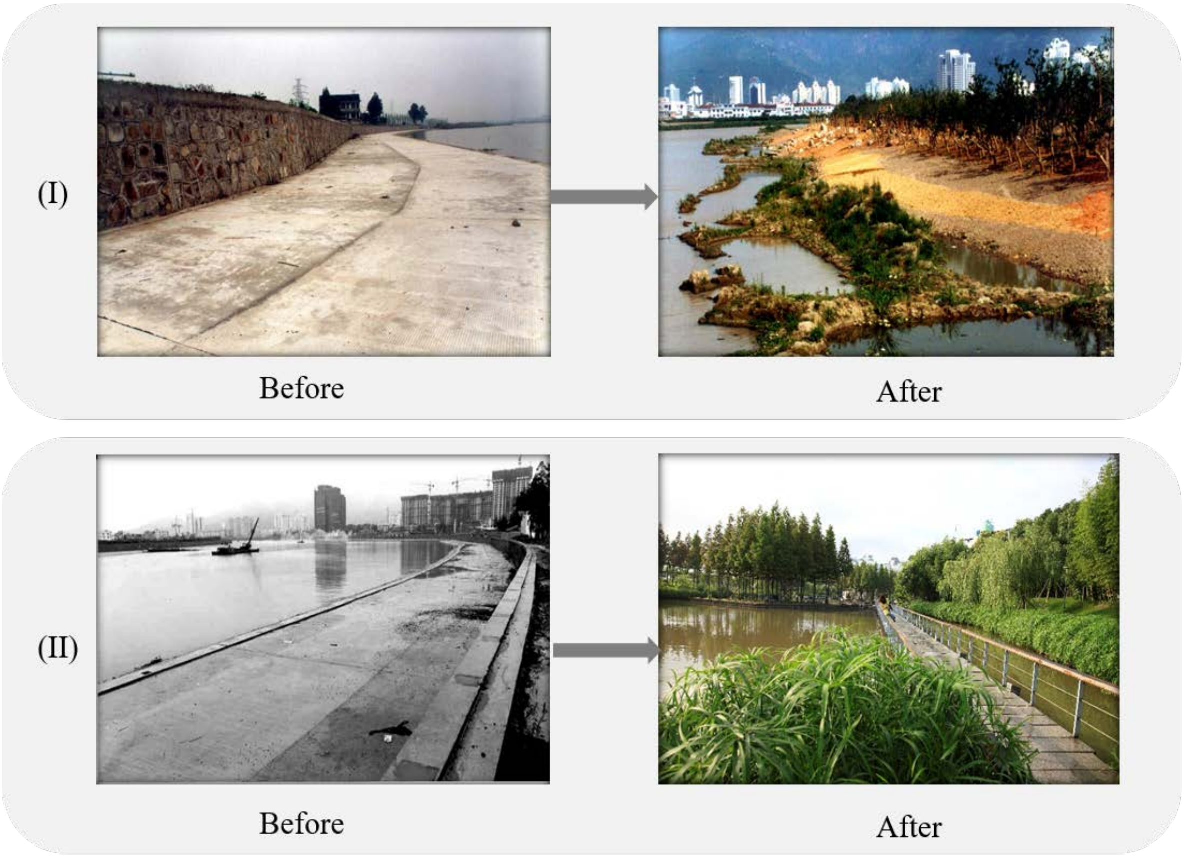


Figure 3. Nature-based solutions from the Chinese GI concept: (I) photos before and after GI design and implementation in the City of Taizhou, China; (II) example of public park beside the Yongning river before and after Taizhou's GI plan (photos adapted from Wang and Banzhaf, 2018, with the kind permission of Prof. Yu (Yu, 2014))

2.2 Theoretical foundations for urban green infrastructure research

GI research has been conducted in several disciplines, including urban ecology (Hostetler et al., 2011; Pinho et al., 2016; Pinho et al., 2014; Qureshi et al., 2013; Qureshi et al., 2010a; Qureshi et al., 2010b), landscape ecology (Breuste et al., 2013; Breuste et al., 2008; Chang et al., 2013; La Rosa and Privitera, 2013), sustainable development (Angelstam et al., 2013; Vollmer and Gret-Regamey, 2013), ecosystems and ecosystem services (Andersson et al., 2014; Lovell and Taylor, 2013; Young, 2011; Young and McPherson, 2013; Zölch et al., 2016). All these ecological disciplines provide fundamentals for GI development and, to some extent, contribute to GI planning and implementation.

Urbanizing cities present substantial challenges to ecosystem ecology. A large number of disciplines and theories focused on the realization of sustainable urban development (e.g. sociology, geography, urban planning, landscape architecture, engineering, economics, anthropology, climatology, public health and ecology) have developed worldwide. Among them, urban ecology, as an ecological method of planning and managing urban areas, has emerged as an interdisciplinary field that examines how human and ecological processes can coexist in human-dominated systems and help societies in their efforts to become more sustainable (Chang et al., 2013; Dobbs et al., 2011; Lafortezza et al., 2013; Muller and Burkhard, 2012; Wu, 2014; Yu, 1996).

All these ecological disciplines provide fundamentals for GI development and, to some extent, contribute to GI planning and implementation. However, these interdisciplinary concepts have customized foci so that research on the benefits, functions and key principles of GI cannot be conducted by making direct use of these findings. Using certain terminologies and definitions without an underlying conceptual hypothesis or specific differentiation may, in my opinion, serve to weaken the effectiveness of GI and its attraction as an innovation, and make it difficult to analyze its multifunctionality. The afore-mentioned concepts and key definitions are set out in Table 1.

Table 1: GI-related concepts and key definitions

Concepts related to GI development	**Key definitions**
Ecosystem services	Benefits humans derive from ecosystems which are produced by interrelations *within ecosystems*. These include supporting, provisioning, regulating and cultural services that directly and indirectly affect people (MA, 2005; TEEB, 2010).
Landscape services	Benefits humans derive from *landscape*, expressed as a structure-function-value chain for informing *landscape development* (Termorshuizen and Opdam, 2009).
Ecosystem functions	The subset of the interactions between biophysical structures, *biodiversity* and ecosystem processes that underpin the capacity of an ecosystem to provide ecosystem services (TEEB, 2010). The capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly (De Groot, 1992), including biotic, *bio-chemical and abiotic processes, within and between ecosystems* (Brussard et al., 1998; Lovett et al., 2005; Turner, 2005).
Landscape functions	The capacity of a landscape to provide goods and services to society. These goods and services are all benefits people obtain from *landscape*, such as *food, fresh water* and recreational benefits (Millennium Ecosystem Assessment, 2003).
Ecological functions	Those that provide services that moderate climatic extremes, *cycle nutrients, detoxify wastes, control pests, maintain biodiversity* and purify air and *water*, among other services (Ecological Society of America, 2006).
Land-use functions (Thellufsen et al.)	Defined as the private and public goods and services provided by multifunctional land uses *at regional scale*, that summarize the most relevant economic, environmental and societal aspects *with specifics for agricultural areas* (Pérez-Soba et al., 2008; Wiggering et al.; Wiggering et al., 2003). As for the differences among ecosystem functions, ecosystem services, landscape functions and LUFs, my opinion is in accordance with Schößer et al. (2010) (pp. 164–168).
Green infrastructure functions	Thus far, they have been grouped as ecological, social and economic functions (Pauleit et al., 2011) or they have followed an alternative classification, such as the abiotic, biotic and cultural functions of green spaces (Ahern). This needs to be rendered much more precisely (see Section 5.2).
Green spaces	Well-structured vegetated pieces of land located in a city with differentiations in vegetation cover. They are one of the most important components of GI, and considered as public goods which allow free access to all citizens and represent pockets of nature for all residents (Banzhaf et al., 2014; de la Barrera et al., 2016).
Landscape sustainability	*Capacity of the landscape* to consistently provide long-term, landscape-specific ecosystem services essential for maintaining and improving human well-being (Wu, 2013).
Multifunctional landscapes	*Landscapes* that provide a range of beneficial functions across production, ecological and cultural dimensions, considering the needs and preferences of the owners and users (Lovell et al.)
Green infrastructure multifunctionality	The ability to provide multiple or cross-cutting functions by integrating different activities and land use on individual sites and across a whole green infrastructure network (Natural England, 2009). The potential for green infrastructure to have a range of functions, to deliver a broad scope

Concepts related to GI development	Key definitions
	of ecosystem services (ibid.). This, too, needs to be rendered much more precisely (see Section 5.2).
Nature-based solutions (NBS)	Nature-based solutions are solutions to societal challenges that are inspired and supported by nature, that are *cost-effective*, that provide simultaneous environmental, social and economic benefits, and that help *build resilience* (Raymond et al., 2017).

(Note: Left column: concepts that need to be rendered more precisely; right column: major differences are highlighted in italics.)

2.3 Indicator-based frameworks for the assessment of multifunctional green infrastructure

For the purpose of the methodology development, three prominent frameworks that reflect the evolution of the GI concept are presented (**Paper I**), while acknowledging that a large amount of research has dealt with individual or groups of indicators when assessing ESS (e.g. (Church et al., 2014; Herzog, 2016; Meerow and Newell, 2017)). The paper sheds light on the most noteworthy frameworks that encompass the primary aspects of GI and that have been designed for and applied to GI development. The three indicator-based frameworks selected are:

Indicator framework I (see Table A1) for ESS assessment, from the MAES report (Mapping and Assessment of Ecosystems and their Services): The indicator-based framework proposed for the mapping and assessment of ecosystems and their services in urban areas – Urban Ecosystems Fourth Report (MAES, 2016, pp 75-81; (Maes et al., 2016b). It is adapted and extracted from the Common International Classification of Ecosystem Services (CICES) with a more urban-focused purpose, namely urban GI and urban ecosystems (ibid.).

Indicator framework II (see Table A2) from the Institute for European Environmental Policy (IEEP): The indicator framework by the Institute for European Environmental Policy (IEEP) was selected, as it is designed to assess various functions (Mazza et al., 2011) provided by different GI types, such as hedgerow, lawn/meadow, agroforestry, etc. I will hereafter refer to it as indicator framework II. It addresses the environmental, social and economic benefits provided across differentiated GI types. Moreover, indicator framework II is intended to support the assessment of urban GI as a possible part of the GI strategy (Mell, 2016).

Indicator framework III (see Table A3) for supporting a shift towards a green economy, from the EMDA: Supporting the transition towards a green economy is a major task for practitioners when putting frameworks into practice. The rationale for every GI investment requires rigorous examination due to economic austerity (Green Infrastructure North West, 2011; Pauleit et al., 2018; Pauleit et al., 2019b). The indicator framework III underscores the economic valuations of GI. I therefore include indicator framework III, as it emphasizes the economic dimension of GI. It was first established in 2008 by the East Midlands Development Agency (Cordier et al., 2014), which expanded the benefits of GI by initiating the awareness of its economic values (Green Infrastructure North West, 2011; Kronenberg and Andersson, 2016). It was then appraised in the study Green Infrastructure Implementation and Efficiency (Mazza et al., 2011) and demonstrated to support the development of green infrastructure strategy in cities. The EMDA addresses the economic valuation of GI as quantitative benefits, including monetary aspects, in its assessment of GI (East Midlands Development Agency (EMDA), 2010).

Because indicator framework I emphasizes the ESS provided by urban GI, indicator framework II provides multiple GI benefit groups and incorporates human health aspects, and indicator framework III adds to these frameworks by focusing on indicators for the economic valuation of GI benefits, they are selected as prominent frameworks for the assessment of multifunctional green infrastructure (AMGI).

2.4 Research needs

2.4.1 Concept of green infrastructure

GI as a concept that identifies key strategies for sustainable urban development has been established since the mid-1990s (Pauleit et al., 2011; Wang and Banzhaf, 2018), although urban GI continues to develop as a research field due to the changing needs of nature and humans in terms of sustainability and staying healthy in the long term. Thus far, GI research has been conducted in several disciplines, including urban ecology (Hostetler et al., 2011; Pinho et al., 2016; Pinho et al., 2014; Qureshi et al., 2013; Qureshi et al., 2010a; Qureshi et al., 2010b), landscape ecology (Breuste et al., 2013; Breuste et al., 2008; Chang et al., 2013; La Rosa and Privitera, 2013), sustainable development (Angelstam et al., 2013; Vollmer and Gret-Regamey, 2013), ecosystems and ecosystem services (Andersson et al., 2014; Lovell and Taylor, 2013; Young, 2011; Young and McPherson, 2013; Zölch et al., 2016). All these ecological disciplines provide foundations for GI development and, to some extent, contribute to GI planning and implementation. However, their interdisciplinary concepts have customized foci so that research on the benefits, functions and key principles of GI cannot be conducted by making direct use of these findings.

2.4.2 Multifunctionality and connectivity in urban green infrastructure

Both the multifunctionality and connectivity are significant principles of urban green infrastructure planning (Hansen and Pauleit, 2014; Pauleit et al., 2011). In recent years, multifunctional GI has been recognized as a condition for sustainability (Brandt J, 2004; Breuste et al., 2015; Zander et al., 2007) and has also been extended to include intensively-managed ecosystems (Harrison et al., 2010; Lovell and Johnston, 2009). A growing number of researchers are emphasizing the importance of multifunctionality as a fundamental property of sustainable development (European Commission (EC), 2012; Maes et al., 2013a; Maes et al., 2013b; Selman, 2009).They have all reiterated that multifunctionality in GI is one of its greatest strengths (Civic, 2014; Davies et al., 2006; Kimmel, 2013).

The core ideas in GI, especially its multifunctionality, are comparatively more specific than those of more abstract concepts such as the complementary "sustainable development". Hansen and Pauleit (2014) provide a comprehensive perspective on evaluating multifunctionality by taking the following aspects into consideration: GI integrity, hot spots, synergies and trade-offs, supply and demand of services, and stakeholder preferences (Hansen and Pauleit, 2014).

In cities, GI consists of planning and designing a multifunctional network of interconnected patches of vegetation cover and permeable soils in order to restructure the landscape mosaic at various scales. For example, trees along streets and riparian corridors may connect parks and other green areas. The aim is to conserve or re-establish key socio-ecological functions and services, with a variety of abiotic, biotic and cultural benefits (Benedict and McMahon 2006; Ahern, 2007; Herzog, 2016). This beneficial esteem comes from ''direct experience with nature [through which] people come to understand its value and gain better appreciation of the importance of healthy habitats and ecosystems'' (Newman and Jennings, 2012). So far, GI multifunctionality has mainly been geared towards biodiversity, floodplain management, local temperature regulation and the provision of public green spaces (Madureira and Andresen, 2014; Connop et al., 2016; Herzog, 2016; Tiwary et al., 2016). In order to address multifunctionality and connectivity in GI principles further, a robust multidisciplinary approach involving multiple aspects of GI functions should address not only the individual and accumulative benefits of each function but also their spatial interactions.

2.4.3 Urban green infrastructure planning for environmental equity

Equity forms a link between social and environmental sustainability (European Commission, 1996). It is thus important to know the levels of equity in order to enhance sustainability between society and environment. Environmental equity is particularly important in urban blue and green spaces, given that these landscapes are highly valued for restorative experiences (Korpela et al., 2010), recreation (Wang et al., 2019a), and perceived health reasons by inhabitants (Korpela et al., 2010, Xu et al., 2018).

Urban GI planning may affect the disparities and distributions of urban green spaces, thereby changing the supply of urban ESS. The role of urban GI planning, therefore, is to guarantee urban inhabitants access to the same level of services, environmental goods and amenities (Heckert and Rosan, 2016), especially those provided by urban public spaces, parks, and leisure spaces (Elvers et al., 2008). On the other hand, understanding environmental equity from a spatial planning perspective may ensure that urban settings (especially green and blue spaces) are designed in ways that contribute to a broad range of experience, such as providing a connection to nature and supporting the diversity of urban habitants’ activities (e.g., speed walking, jogging, cycling) (Raymond et al., 2016).

Thus, as significant strategies for urban sustainability, urban GI planning should strive to achieve a relatively equal socio-ecological development/change (Pincetl and Gearin, 2013) by balancing disparities in the distribution of GI and its ecosystem services (ESS).

2.4.4 Urban green infrastructure mapping

Urban GI mapping methods are fundamental to urban planning, providing a strong evidence base which may ultimately facilitate the development of recommendations on how to plan and strategically manage GI assets in order to improve GI functions (Hansen, 2018).

My findings show the typology of GI mapping approaches and tools that is widely employed (Dan, 2012; European Environment Agency (EEA), 2011; Lovell and Taylor, 2013; Maes et al., 2013b; Schägner et al., 2013; EEA, 2014). These types of GI mapping approach include

- GI using the Urban Atlas; GI using CORINE Land Cover, or
- a combination of Natura 2000 and other land-use and land-cover (LULC) datasets;
- GI and landscape fragmentation models;
- GI and net landscape ecological potential (NLEP);
- GI using morphological spatial pattern analysis (MSPA);
- GI and mapping of ecological corridors;
- GI and CORINE, especially ecotones or protected areas;
- GI mapping by means of the Quickscan software module, integrated Geographical Information System (GIS) or other tools;
- GI using regional environmental characterization or integrated modeling tools.

As an outcome, these approaches are complementary and provide information from more than one input data source, e.g. fragmentation (EEA, 2014), land use and land cover (Urban Atlas), coordination of information on the environment (spatial analysis), etc. As for the enclosed scales, the respective GI mapping methods encompass the continental (including pan-European), international, national, sub-regional, urban and local (including sites, neighborhood and community) scales.

To highlight one type of functional mapping as a way of providing an insight into GI, morphological spatial pattern analysis (MSPA), which accounts for about 6% in this review (see Table 1) and is based on mathematical morphology (Soille, 2003), identifies hubs and links from a single land-cover map rather than overlaying several maps in a GIS. In doing so, it distinguishes structure from the spatial relationships existing among different land-cover features (Wickham et al., 2010; Ramos-Gonzalez, 2014). In the national assessment of GI research by Wickham et al. (2010), for example, MSPA is highly advantageous because it explores GI configuration and structural connectivity by extending the geographic scope and incorporating land-cover change information. As part of this information, GI mapping using MSPA can be applied in guiding conservation and restoration decisions (e.g. loss of bridges signifies lost connectivity, which can potentially be used to prioritize restoration).

2.4.5 The challenges in the assessment of multifunctional green infrastructure

As the concept of ESS is fundamental to an understanding of GI, it is applicable at a range of scales. Some authors present the benefits of GI in the light of ESS because the latter provide a relatively consistent and effective language that is enjoying a growing resonance among policy makers and other stakeholders (e.g. Naumann et al. (2011a), Plieninger et al. (2013), Kukkala and Moilanen (2016), Willcock et al. (2016)).

However, the connections between GI, ESS and natural capital have not been made explicit since the concept of GI first emerged (Garmendia et al., 2016). The functions associated with GI lend the concept distinctiveness and add value in comparison with the more general and implicit descriptions of ESS. In my opinion, the specific and explicit functions of GI ought to encompass the spatial targets of ESS – hereafter, GI implementation – their spatial connectivity and specific indicators for assessing the effects of GI implementation (European Environment Agency (EEA), 2011).

In academic research, ESS classifications are slowly being transferred into GI analysis. Typical GI classification methods are underpinned by the widely accepted conceptual framework of ESS (EEA, 2011; EC, 2012; 2014; Liquete et al., 2015; Maes et al., 2015; Kopperoinen et al., 2014). For instance, the *Liverpool GI Strategy Action Plan* (version 1.0) assessed six priorities, subdividing these into 28 GI functions, ranging from those related to managing water, such as water interception and storage, to others referring to recreation, aesthetic and carbon sequestration functions (TMF, 2010). Its subsequently updated *GI Framework Technical Document* (version 1.2) points to GI multifunctionality and includes the aims of enhancing the ecological framework and developing the rural economy, but its shortcoming is that it assesses only *four* priorities (i.e. [in italics] *setting the scene for growth; supporting adaptation to climate change; providing recreation, leisure and tourism; supporting health and well-being* (TMF, 2013)), even though substantial progress in multifunctionality analysis has been made for each of these priorities from version 1.0 to 1.2. In terms of a GI multifunctional assessment, further research is still required: when it comes to pragmatic implementation, policymakers may wish to consider weighting their policies towards the protection of GI functionality in urban areas. A weakness is that no underlying version introduces weighting or relates GI functions to the demand for GI benefits from a social perspective. The latter is, however, regarded as an essential aspect when assessing multifunctional GI (Hansen and Pauleit, 2014).

There are inevitable difficulties in GI assessment, since GI assessment depends on an integrative indicator framework of GI multiple functions obtained by benefit groups. Even though it is worthwhile mentioning that these plans demonstrate the high potential of the GI concept to deliver multiple benefits to society, they do not devote enough consideration to multiple functions to be able to contribute to GI assessment. Consequently, they fail to establish anything that will be productive for GI strategy, let alone for its network and multifunctionality. Multifunctionality must be considered as one stage in the decision-making process in which we necessarily make choices among functions.

In the first doctoral phrase (GI concept analysis), I found that most of the papers in the ISI Web of Science specifically deal with multifunctional GI assessment (Wang and Banzhaf, 2018), yet only one emphasizes the importance of multifunctionality in urban GI. However, even this one study puts forward only two indicators (i.e. local temperature regulation and population proximity to public green spaces), even though it eventually comes to the crucial conclusion that a shift from generic assumptions to local assessment may help understand and analyze GI evolution (Madureira and Andresen, 2014). Although this study gives a localized sample in multifunctional GI analysis, it obviously fails to make a more synthetic assessment, since some other essential functions of GI (such as recreation, sense of place or enhanced biodiversity) are not considered. Overall, this thesis upholds the view that urban GI is multifunctional in that it addresses geologic, hydrologic, biotic, circulatory, social and metabolic systems, besides stimulating economic development (Herzog, 2016).

2.4.6 Gaps in current assessment frameworks

Since GI has been recognized as a concept only relatively recently, and strategic planning is relatively new – both have emerged over the past 20 years –, studies devoted to a thorough assessment of urban multifunctional GI, either with a long-term focus or at multiple spatial scales, are rather rare (European Commission, 2012; European Environment Agency (EEA), 2011).

Given that a systematic combination of several indicators is the best way to represent the overall performance and functions of GI (European Commission, 2012; Naumann et al., 2011b), frameworks and methodologies have recently emerged that aim to assess multifunctional GI through indicators (e.g. (Maes et al., 2016a; Maes et al., 2013a; Maes et al., 2014; McDonald et al., 2005; Wright, 2011). In this context, it has been recognized that a better understanding of multifunctional GI is crucial for sustainable urban development (Pauleit et al., 2019b; Zhang et al., 2019). Indeed, there is a growing number of frameworks (e.g. (Cordier et al., 2014; East Midlands Development Agency (EMDA), 2010; Gordon et al., 2018; Maes et al., 2016a; Maes et al., 2016b; Mazza et al., 2011; Naumann et al., 2011b; Niemeijer and de Groot, 2008), and most studies have provided useful insights into GI assessment. For example, the Common International Classification of Ecosystem Services (CICES) supplies a set of indicators on the basis of a cascade structure (i.e. provision, regulation and cultural services (Haines-Young and Potschin, 2010) in order to support ESS assessment (Maes et al., 2016a; Rocha, 2015). Furthermore, *The Economics of Ecosystem Services and Biodiversity* (TEEB) (TEEB, 2010) have considered the (Ecosystems and Biodiversity) values of ESS, building upon the Millennium Ecosystem Assessment (MEA) (Millennium Ecosystem Assessment, 2005). As an advancement, the indicator frameworks from the *Total Economic Value* concept by Vandermeulen, et al. (Vandermeulen et al., 2011) and the GI valuation toolkit by the East Midlands Development Agency (EMDA) in 2008 have recognized a range of GI values. These include direct use values (e.g. the supply of food and water), indirect use values (e.g. air and temperature regulation) and non-use values such as protection for future generations (Ten Brink and Tekelenburg, 2002).

However, these frameworks are mainly restricted to a fractional GI assessment, such as cultural services provided by GI, or to a limited number of GI functions (Wang and Banzhaf, 2018). Less is known regarding their spatial extents and their coverage of qualitative assessment or quantitative measures. It is thus hardly possible to obtain a full picture of multifunctional GI or to undertake a multifunctional GI assessment of only one ESS or GI function. Moreover, the role of urban multifunctional GI in promoting ESS (European Environment Agency (EEA), 2011) and societal health and well-being (European Commission, 2012), supporting the development of a green economy (Davies et al., 2015; Pauleit et al., 2018; Pauleit et al., 2019b) and fostering sustainable land and water management ought to be reflected in the indicator framework in order to guide GI planning, management and policy-making. The challenge remains, as there no integrated indicator framework that enables scientists and practitioners to undertake an individual assessment of multifunctional green infrastructure (AMGI), particularly as regards primary aspects of urban GI, such as ESS provided by GI (Maes et al., 2016b), the multiple benefits and functions of GI (European Commission, 2012), and the potential (monetary) value of GI functions (Green Infrastructure North West, 2011; Madad et al., 2019). As such, AMGI requires a combination of qualitative or quantitative assessments and quantitative measures, using input from both ecological and social sciences (European Commission, 2012; European Environment Agency (EEA), 2011). In the absence of an integrated indicator framework for multifunctional GI and a methodology for conducting AMGI, the AMGI is inclined to be selectively conducted (Hansen et al., 2015; Rall et al., 2015) and thus might lead to a slow uptake of GI in practice (Nielsen et al., 2016; Rall et al., 2015). Furthermore, this results in the bias that GI, as strategic planning, may address either too few functions or only limited dimensions of sustainability. When providing a methodology for undertaking AMGI using an indicator framework, therefore, it is essential to be aware of the central indicator frameworks for GI assessment that are capable of conveying the aforementioned major aspects of the urban GI concept, because such an indicator framework can only be valid and circulated further if it can be applied to various cases.

2.4.7 Main methods of spatial patterns analysis

Evidence has emerged in support of the claim that spatial patterns of built-up structures are influencing functional connectivity (Saura et al., 2011; Vogt et al., 2009; Vogt et al., 2007; Wickham et al., 2010) and therefore the provision and functioning services of GI (Alberti, 2005; Bierwagen, 2005; Cavan et al., 2014; Tratalos et al., 2007; Vogt et al., 2009; Whitford et al., 2001). This therefore necessitates further and more in-depth studies concerning spatial patterns and their effects on biodiversity and urban ESS (Alberti, 2005).

To describe the spatial patterns, various methods and tools have been developed and applied in urban ecology (e.g. McGarigal and Marks (1995); Kim and Pauleit (2007) Kuttner et al. (2013) with the aim of revealing the links between urban GI patterns with ecological and social functions (Luck and Wu, 2002). They comprise methods such as Fragstats (Luck and Wu, 2002; McGarigal et al., 2002; McGarigal and Marks, 1995), which provides a series of landscape metrics (e.g. area/density, patch shape index and proximity metrics) for detecting the urbanization gradient of landscape patterns (Kupfer, 2012; Luck and Wu, 2002) and biodiversity conservation (Kim and Pauleit, 2007). In addition, tools such as least cost measures (Sutcliffe et al., 2003) and genetic patterns offer a more ecologically oriented approach to quantifying spatial patterns (e.g. Chardon et al. (2003); Coulon et al. (2004); Hokit et al. (2010).

Other graph-based approaches are also applied, for instance, the Conefor Sensinode tool (Saura and Torne, 2009), quantifying habitat patches for connectivity by calculating nodes, links and graph-based metrics, including the number of links, the number of components, the integral index of connectivity, and so on; or the Circuitscape tool (McRae and Shah, 2009), which makes it possible to calculate and map measures of resistance, conductance, current flows and voltage. These are widely utilized to analyze structural landscape metrics and connectivity, but they are all rooted in graph, network, and circuit theory (Kupfer, 2012), being limited by inconsistent evaluation results from human interpretation (Kupfer, 2012; Ostapowicz et al., 2008). Their definitions of thresholds such as patch width are in terms of selected contexts.

Accordingly, the great challenges apparent in the methods used to analyze spatial patterns are: the former, i.e. structural indices of patch shape such as perimeter to area ratio, and the latter i.e. graph-based approaches which can explore the importance of corridors as connectors between nodes (Ostapowicz et al., 2008) in a network, but only after these corridors have been defined elsewhere.

METHODOLOGY

“It is actually not painful to learn something,
if you do it incrementally."

(Yoyo *Ma)*

3 Methodology

3.1 Research design

This dissertation specifically examines the multifunctional GI concept, aiming to enhance GI planning and assessment of urban GI guided by its latest conceptual development, as shown in Figure 4. At the beginning of this doctoral project, the focus of this thesis was divided into three aspects: the GI concept, the assessment of multifunctional GI, and GI planning via enhancing the spatial connectivity of green spaces. These are all in line with the GI conceptual evolution, as established in the first stage of this dissertation.

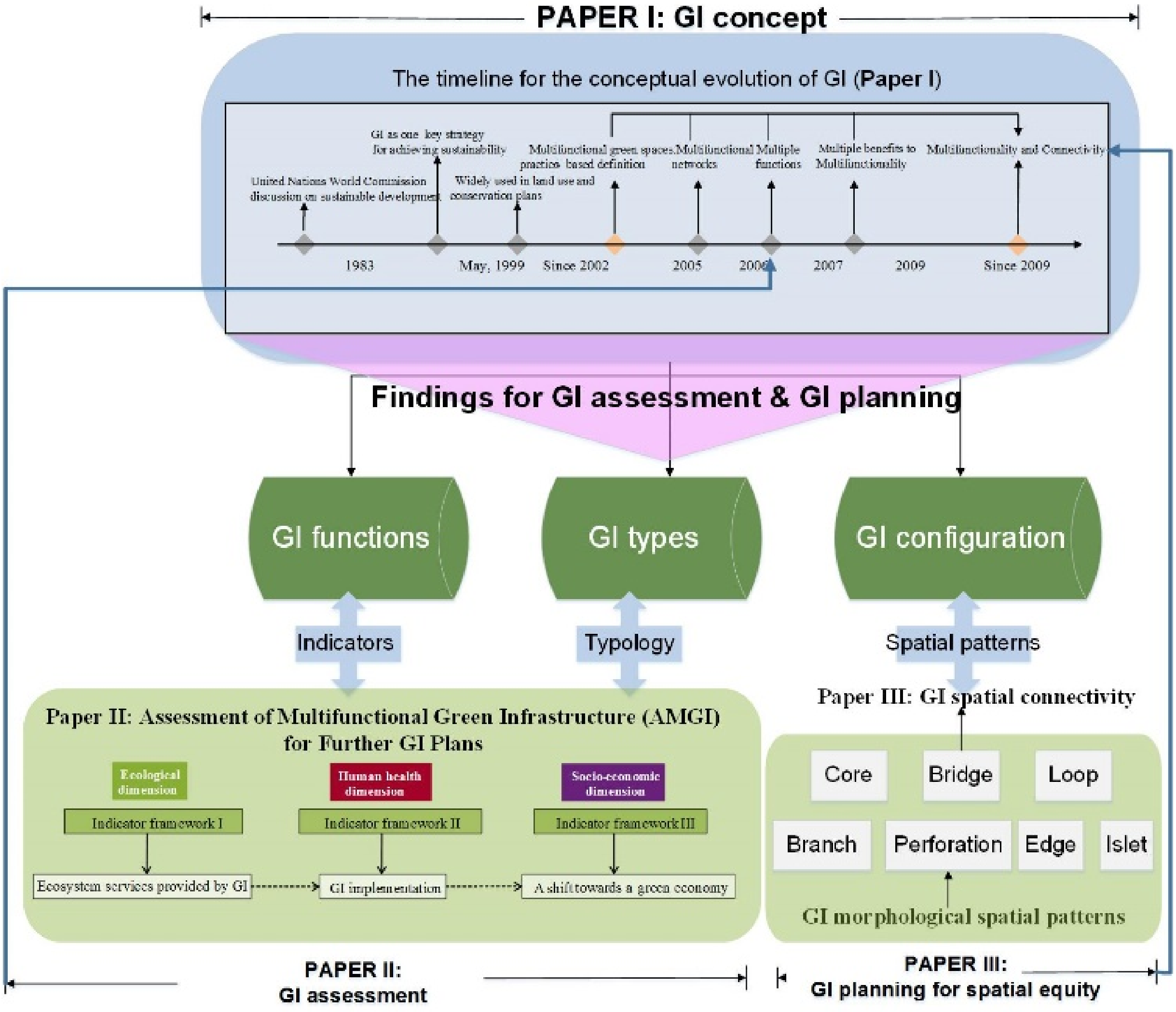


Figure 4. Research design of this thesis: the conceptual development of urban GI (Wang and Banzhaf, 2018; Wang et al., 2019a)

The GI concept and its application in GI assessment and planning can be addressed via three aspects: GI functions, various GI types and the GI configuration. The research design specifically aims, therefore, to address these three significant aspects in the case studies. The first case study in Paper II has underpinned the objective of this thesis by proposing indicators for GI functions and coming up with a comprehensive GI typology from gray to green spaces. As for the GI configuration analysis, another in-depth case study was designed based on the comprehensive understanding of the case area, Leipzig. Several typical samples were selected in the morphological spatial patterns analysis. The GI spatial connectivity (a highlighted milestone in the GI concept in Paper I) was improved using GI core, bridge and loop patterns within the typical residential areas (Wang et al., 2019b). Overall, both of the case studies in Paper II (GI assessment) and Paper III (GI planning) underscored the multiple GI functions and GI connectivity respectively, as shown in Figure 4.

3.2 Qualitative methods

3.2.1 Literature review in Paper I

To make the literature review for the GI concept as integrative and exhaustive as possible, a wide range of relevant sources was examined in order to find meta-analyses of published scientific papers. Figure 5 illustrates my database structure, designed to meet my research objectives (i), (ii) and (iii).Up to October 31, 2016, the following databases were searched for full journal and peer-reviewed articles as well as technical reports and guidance, using a broad range of search terms and Boolean operators (e.g. Urban AND green infrastructure AND multifunctional OR assessment, green spaces AND multifunctional etc.) and setting the search timespan as all years: 1) Web of Science database; 2) Scopus; 3) Google Scholar database; and 4) China National Knowledge Infrastructure (CNKI).

One novel – and necessary – aspect is that the review includes Chinese research results, although English is the principal language of international academic publications (e.g. Alavipanah et al. (2017); Ziter (2016) and my major point of reference. It is important to illuminate publications from Chinese research because Chinese urbanization and the related ecological pressure are globally unprecedented. In most reviews undertaken so far, Chinese publications have been understood to be useful on the basis of their abstracts (many articles published in key Chinese journals have English abstracts but are otherwise written in Chinese) and have been included from 1975 onwards (Alavipanah et al., 2017; Haase et al., 2014). As the actual studies of these Chinese articles are not published in English, they could not be included for further detailed analysis by the afore-referenced authors. Some Chinese research into GI (e.g. the China Sponge City concept and Turenscape GI design) is therefore considered to be an innovative and proactive response. An urban planning instrument such as the Taizhou city plan (2006) designed by Landscape Architect Kongjian Yu and a research team at Peking University, and multifunctional GI planning research in Haidian District, Beijing conducted by Prof. Yu's research team (2013) at China Agricultural University (Liu et al., 2014), both serve to elucidate GI guidelines with respect to connectivity and multi-purpose water systems (Ahern, 2007).

The global search covered the topic area (Figure 5: topic database) of GI and returned more than 467 unique records. The title of each paper and the executive summary of each report were first carefully checked for relevance to 1) the GI concept and 2) the GI mapping approach on the basis of their abstracts. A large number of publications (114) on ecosystem services (ESS) assessment were deliberately included in this review database to provide a robust basis for considering mapping tools with potential relevance for GI.

Overall, out of a total of 440 articles, 139 studies had to be discarded, leaving 301 articles to be included in my in-depth analyses. The database of this review on GI research publications is run by two software packages, namely, Endnote X7.1 and CNKI E-learning 2.1 (see the catalogue of my review database in Figure 5).

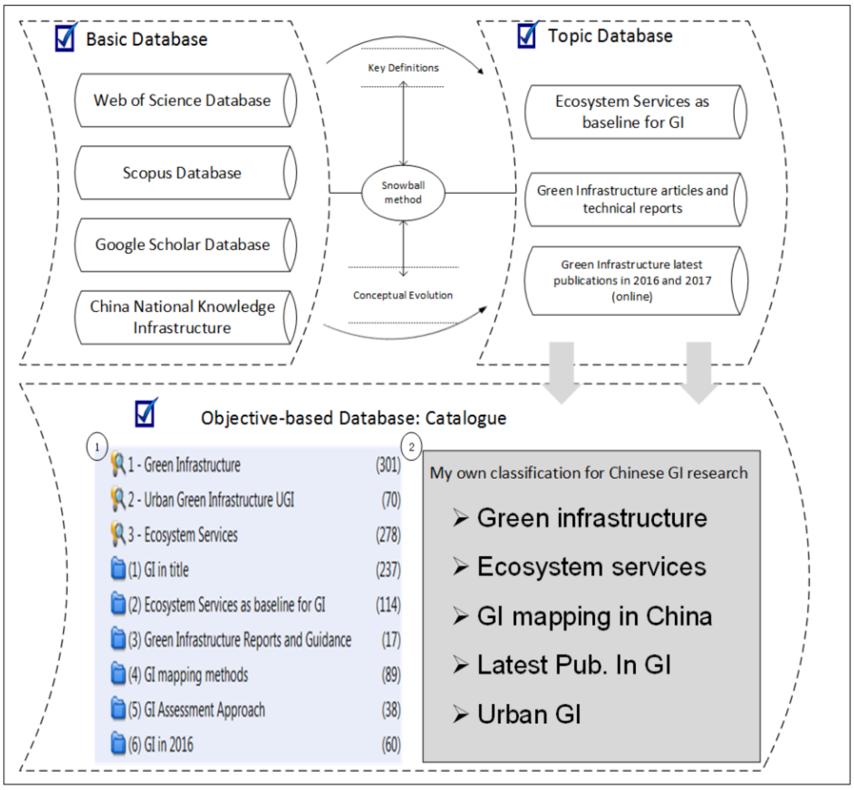


Figure 5. Entire database management for basic, topical and objective-based catalogues (adapted from Wang and Banzhaf (2018)

A ‘snowball method’ of literature review was conducted, starting with the reference lists of key articles and documents (Mouton and Babbie, 2001). Where key documents cited other literature, the original source of information was acquired and reviewed. Literature referenced in the reviewed papers was added to this GI research database. For example, some ESS can be provided by GI, and so we included the related ESS publications and filtered them carefully according to their services (Figure 5).

3.2.2 Analysis method for selected indicator frameworks

In the following, each indicator from these indicators frameworks is scrutinized with regard to 1) relevant spatial extent, 2) GI types involved (service provision units), 3) data availability, 4) their information regarding GI assessment (e.g. data sources and references/proven methods), and 5) whether it is a supply indicator or a demand indicator, by means of reviewing each indicator from its source listed in the respective framework (from the MAES, the IEEP and the EMDA) as well as other potentially updated studies on *Web of Science*, *Scopus* and *Google Scholar* databases.

Since **indicator framework I** only follows the structure provision, regulation and maintenance, and cultural ecosystem services, all indicators have to be classified into various GI benefit groups (Table 2) to allow for further comparison with the other two frameworks in the following sections. For classification purposes, we use the definitions of each GI benefit from indicator framework II and III. The corresponding relationships between ESS (provisioning, regulation and cultural services) and GI benefit groups are listed in Table 1 (code numbers refer to the respective indicators in Table A.1).

Whenever the specific purpose of one of these 40 indicators was not clear or related to more than one dimension, we traced it back to its source and compared it carefully with the definition of relevant ecosystem services in CICES V5.1 (Haines-Young and Potschin, 2018) (the latest version released on January 2018) and the second (Maes et al., 2014) and fourth reports (Maes et al., 2016b) of MAES: *Indicators for Ecosystem Assessments under Action 5 of the EU Biodiversity Strategy to 2020 and Urban Ecosystems*. Apart from tracing back the original sources of the framework as such, we also reviewed each indicator in turn with regard to their reference sources in order to understand which dimensions the respective indicator had employed in addressing sustainability.

The structure transformation of **indicator framework I** facilitates its further comparison with the other two frameworks, since both **indicator framework II** and **indicator framework III** have already been divided into ten GI benefit groups by Mazza et al. (2011).

Table 2: Transformation of the structure of indicator framework I into different GI benefit groups (indicator codes refer to Appendix Table A.1, adapted from Wang et al. (2019a)

MAES classes	GI benefit groups	Indicator codes from indicator framework I
Provision	Natural resources	01, 02, 05, 28, 29
	Water management	03, 04, 06
Regulation and maintenance	Climate regulation	07, 08, 10 to 16, 18, 20, 21
	Health and well-being	09, 17, 19, 26
	Resilience	22, 23, 24, 25, 27
Cultural	Tourism and recreation	30 to 38
	Education	39
	Conservation benefits	40

(* The GI benefit health and well-being relates merely to the indicators for human exposure, in alignment with the definition from the final report on GI implementation and efficiency by Mazza et al. (2011), although health and well-being are closely connected with cultural services. With regard to the definitions for GI benefits, this is in line with the source of indicator frameworks (ibid.).)

3.3 Analysis methods of multi-source land-use/land-cover datasets

3.3.1 Spatial datasets for the exemplification in Leipzig, Germany (Paper II)

Three earth observation datasets were used in **Paper II** for the illustrative case of Leipzig:

(1) The land-cover data originated from the European Urban Atlas land cover dataset – Copernicus Land Monitoring Service. It stems from the European Environment Agency (EEA, http://www.eea.europa.eu/data-and-maps/data/urban-atlas). For the first time slot, the Urban Atlas data (2006) conveys 305 larger urban zones (including commuting zones around cities) in the 27 countries of the EU for all European core cities and respective larger urban zones with more than 100,000 inhabitants. Its products are combined image classifications with 20m (SWIR mode) to 10m (NIR and visible spectral) multispectral analysis for urban GI, being pan-sharpened to 5m to 2.5m spatial resolutions. The more recent slot, i.e. UA data for 2012, covers all European cities with a

minimum of 50,000 inhabitants. Our application in Leipzig used the Urban Atlas data from 2012 (Wang et al., 2019a).

(2) The Leipzig biotope mapping (2005) was extracted from the biotope map of Saxony. Its structure is similar to that of the Urban Atlas, as it includes both human-built classes as well as natural and semi-natural classes (Sächsisches Landesamt für Umwelt Landwirtschaft und Geologie, 2008). However, the dataset is derived from 1:10,000 color-infrared orthophotos by the manual classification of biotopes with a minimal area of 0.25 ha (ibid.). This thematic information was produced by the "Sächsisches Landesamt für Umwelt Landwirtschaft und Geologie" (2008). Its classification system of biotope types provides abundant information on diversified sites and biotopes in urban areas (Werner and Zahner, 2010). Biotope mapping characterizes landscapes, especially in urban areas, as a complex habitat mosaic (Mazerolle and Villard, 1999), which is made up of various sub-units and forms. These are major components in the evaluation of GI functions. This classification of urban spatial categories and matrix-patches mapping (Mathieu et al., 2007) may extensively facilitate the identification of several GI features such as deciduous forests and zoological gardens, whereas other datasets such as Corine Land Cover cannot provide sufficient information on urban GI, due to their coarse spatial resolution or relatively rough taxonomy.

(3) The local land-use and land-cover (LULC) structural analysis for Leipzig in the year 2012 (Banzhaf and Kollai, 2018; Banzhaf et al., 2018). To gain the spatial information on urban LULC at a very high resolution, 4-band color infrared digital orthophotos (DOP) were employed, a digital elevation model (DEM) and a digital surface model (DSM). These datasets were processed via an object-based image analysis (OBIA) approach. The complex methodology of this OBIA mapping process is depicted by Banzhaf et al. (Banzhaf et al., 2018; Wang and Banzhaf, 2017), who rescale the different datasets to 1 meter ground resolution for the year 2012. As for the demographic data, we employed the population data for 2012 collected by the city council (Stadt Leipzig, 2012), which includes all urban residents with their first and second place of residency in Leipzig. By including those with a second residency, we also take into account international students, commuters, etc., which gives us a better picture of the real users. The respective usages of the three aforementioned earth observation datasets can be found in Table 2.

3.3.2 Land-use and land-cover data for Paper III

To gain spatial information on the urban land use and land cover, we employed digital orthophotos (DOP), a digital elevation model (DEM) and a digital surface model (DSM) at very high resolution. These datasets are processed in an object-based image analysis (OBIA) approach described by Banzhaf et al. (2018), who rescale the different datasets to 1 meter ground resolution for the year 2012. The advantage of this dataset is not only its scale but also its three-dimensional classification scheme and refined categories. The categories comprise urban built and green structures, including green cover types such as trees, shrubs/young trees, lawn/meadow, agriculture and water, providing information on the typical residential areas explained in a previous study (Banzhaf et al., 2018). The object-based classification therefore facilitates the research in two ways: first, it allows us to analyze morphological patterns of GI at very high spatial resolution; and second, it enables us to extract typical residential areas for the analysis of GI in terms of equity and connectivity.

3.4 Mapping and spatial analysis methodology for urban green infrastructure

3.4.1 Overlay analysis in Paper II

Given the small distortion, the popularity of the UTM system and the possibility of international comparison, the Urban Atlas dataset (2005), the biotope mapping (2005) and the local LULC dataset (2012) were transformed into GCS-ETRS-1989 with the Universal Transverse Mercator projection (UTM-Zone-33N) as preprocessing procedures for the AMGI in Leipzig. All these georeferenced remote sensing (RS) datasets were used to identify the enclosed GI features, thereby deriving respective indicators of various GI functions (Table 2). Based on these RS-based products, an overlay analysis of multifunctional GI areas was further undertaken in order to identify the hot/cold spot areas. For the spatial analysis and methods for the identification, we followed the steps introduced in Section 3.4.2.

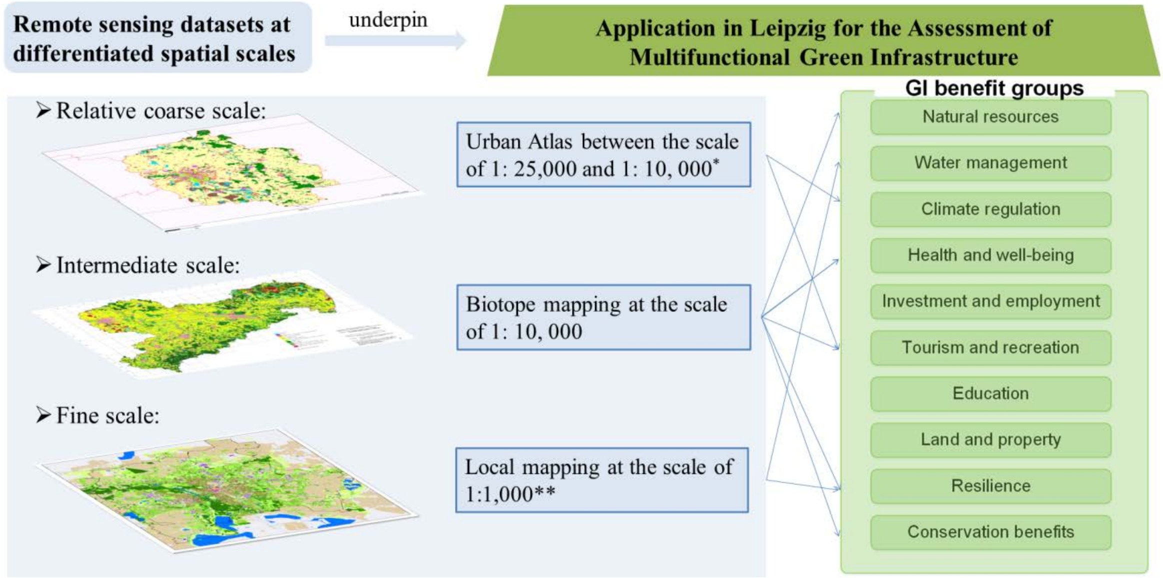


Figure 6. Remote sensing datasets from relative coarse, intermediate, to fine scale as supportive tools for the AMGI in Leipzig (Wang et al., 2019a)

In the application to Leipzig, as shown in Figure 6, the Urban Atlas dataset (2012) was used to obtain information on the population without urban green spaces within 500m distance in their neighborhood using the RS-based method proposed by Poelman (Poelman, 2018). It was also used to resample the remotely sensed thermal data in Leipzig to evaluate the cooling effects of GI using the method introduced by Schwarz et al. (Schwarz et al., 2012). The thermal data refers to the land surface temperature acquired during the two overhead flights on 22 (7:30–9:00 pm) and 23 (5:00–6:30 am) September 2010 at 2000m above ground, within a spatial resolution of 5m (ibid.). The biotope mapping (Figure 6) contributes substantially to obtaining indicators for the assessment of GI functions, e.g. urban recreational areas such as zoological and botanical gardens. As for the local LULC dataset, it was employed to assess GI benefits in water management by providing higher accuracy on the identification of water areas and green areas with water courses.

3.4.2 Methodology for assessment of multifunctional green infrastructure at urban scale (Paper II)

Conducting an AMGI at multiple spatial scales is important if we are to fully capture the benefits of GI and understand the interlinkages between GI at these scales. My selected frameworks I to III were organized into ten GI benefit groups (see Figure 7), which is important for developing a methodology for an AMGI. These ten benefit groups are defined in GI by Mazza et al. (2011).

Pre-evaluation comprises the definition of a specific research question in line with the planning issue at hand, revision of the effective (and planned) policies, and collection of relevant data. Both the GI benefits and multi-dimensions of sustainability comprise the main content of the conceptual framework. The background information for the collection of respective policy and evidence as well as research questions and planning issues in case studies are the first step of the AMGI, i.e. the pre-evaluation. As shown in Figure 7, it contains the multifunctionality and the multidimensionality of sustainability. In both steps, the pillars of sustainability (United Nations (UN), 1996), comprising the dimensions ecology, social economy, social culture and human health, are reinforced and considered as cross-cutting issues. These have to be addressed and taken into consideration in the assessment process. Table A1 to A3 and supplementary materials facilitate these steps.

However, it requires great effort to conduct the entire assessment at all scales simultaneously, since so many aspects (see Figure 7) have to be taken into account. Focal scales must be prioritized depending on the purpose of the use of the indicator-based framework. For example, is it to support a city-wide strategy or is it for planning tools at a more detailed level? Which criteria are vital, which spatial extent is meaningful, which data is available, and what has been investigated in the AMGI (either supply or demand in terms of GI)? Conducting such an assessment is an intricate process, so I developed an integrative approach that allowed me to derive three stages of evaluation, illustrated in a methodological workflow (Figure 7).

Three stages are involved in conducting an integrative assessment on multifunctional GI. These are:

1) Stage 1: Priority setting, including multifunctionality and the multidimensionality of sustainability.

As a prerequisite of this stage, the key strategy and policy documents on spatial planning ought to be assessed as evidence for priority setting. In this first stage, users of an indicator framework should figure out their needs from two perspectives. First, they should decide on the needs for addressing multifunctionality. Users may select the priorities of GI functions from the ten benefit groups (in the green box: from natural resources to conservation benefits). Second, users should be aware of the multi-dimensions for sustainability addressed (in the purple box: ecology, social economy, social culture, human health dimensions). Multidimensional analysis can be completed with reference to the recommendations provided in Table A.1 to A.3. In this conceptual framework phase, the emphasis is that the multiple GI functions and multi-dimensions are interactive and necessary.

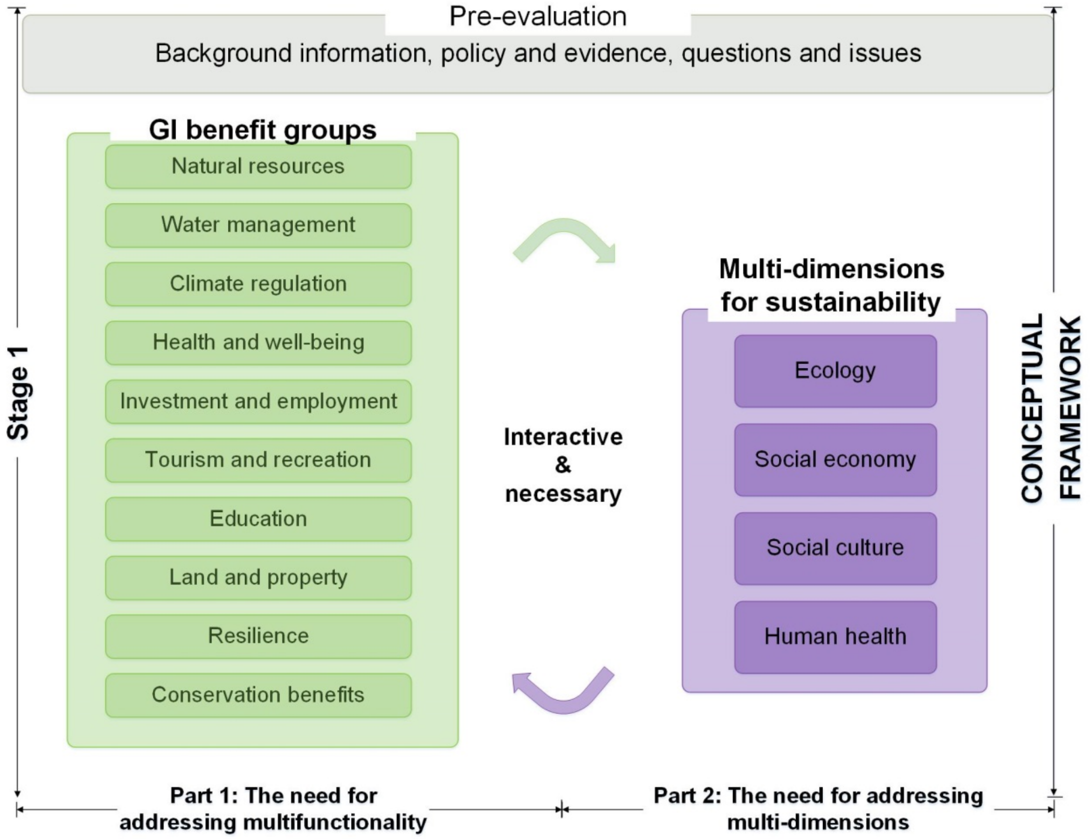


Figure 7. Flow chart of AMGI stage 1: for priority setting (adapted from Wang et al., 2019a)

2) Stage 2: Contextual assessment, including framing the indicator selection

Once the priorities of GI functions and targeted dimensions for sustainability are settled, there are three key factors in indicator selection (i.e. measurement scales, data availability, and either the supply or the demand of ESS is targeted to be estimated). These are the determinants for users' decision-making. To facilitate the decision-making while using our integrated framework, I provide related information in the Supplementary Materials (Wang et al., 2019a). This information is not as comprehensive as to be applicable to all situations, because the selection of indicators depends on the research question, the cultural context of the case study and related data availability. Still, it provides evident references and a useful methodology for a decision-making process.

In Stage 2, there must first be a scientific understanding of which spatial scale(s) is/are vital when assessing GI functions – this is referred to as the focal scale. In my approach, I provide recommendations on four scales for spatially explicit indicators as references: regional, metropolitan, urban and site scales (see the synthetic analysis in Supplementary Materials Text S1). For the purpose of covering integrative GI functions, GI assessment can be conducted at multi-scales, as long as users are aware of the potentials and restrictions of this approach. Due to indicator selections, these potentials and restrictions might be in the process of upscaling or downscaling, and there may also be limitations due to data availability in the respective contexts. In case of lack of quantitative data in contextual assessment, upscaling or downscaling of data can be used as proxies, and qualitative methods (e.g. narratives) can be employed to describe GI functions. Although a thorough understanding of the balance between supply and demand is important, it might be helpful for the sake of the study just to focus on one of the two aspects.

3) Stage 3: Retrospective assessment

The following five elements correspond to five procedural questions for retrospection:

- Which kinds of GI functions have been evaluated?
- Which kinds of GI types have been involved in the stage of contextual assessment compared to my comprehensive GI typology? (see Appendix B, ordered by the intensity of human influence on GI), which is adapted from the urban GI Components Inventory from the Green Surge project (Kabisch et al., 2015)
- Overall, which dimensions of sustainability have been addressed?
- Are supply and demand indicators balanced in the particular contextual assessment?
- If not: Is it still scientifically sound if, in the end, evaluations were not able to reach a good balance due to limited data availability? It could be acceptable on the condition that the extracted results are well distinguished by referring either to the supply or demand of ESS.

After completing the analysis above, users are able to draw conclusions from the evaluation of the GI functions, their relationships with the GI types involved, and the multi-dimensions addressed; this enables them to figure out the multifunctioning GI in respective contexts.

To better understand and visualize the multifunctionality of GI, I suggest using the measurable indicators provided in the previous stage. Using those, GI functions can be overlapped in order to explore whether one spatial unit provides multiple GI functions at the same time. These areas could be defined as multifunctional GI. The areas with three or more types of functions (Peng et al., 2019; Willemen et al., 2010) could be defined as multifunctional GI hot spots using the method by Peng et al. (2019). In other words, those units, e.g. grids, with three or more GI functions spatially form a range of high-possibility clusters of GI functions.

To gain insight into each GI function, I also recommend identifying the hot and cold spots of evaluated GI functions from Stage 2 in a respective contextual assessment. I therefore recommend employing one new index, namely the Getis Ord Gi* statistics – one of the most widely used indicators of local spatial autocorrelation (Chainey, 2010; Getis and ORD, 1992; Manepalli et al., 2011; Peng et al., 2019) – to detect the spatial aggregation of each GI function in terms of its spatial weight matrix, by identifying the respective GI within values higher than others as the hot spots, and within values significantly lower than others as the cold spots.

$$G_i^*(d) = \sum_{i=1}^{n} w_{ij}(d)x_j / \sum_{j=1}^{n} x_j \tag{1}$$

G_i^* can be used to characterize the GI functions and their spatial correlations with the neighboring areas at a defined distance. In this equation, w_{ij} is symmetrically normed from one to zero as a spatial weight matrix, with one for all grids at a given distance d of cell i, including the cell i itself, and zero for the other grids. In this case, the numerator is the sum of all the values of specific GI functions associated with the grids at the distance *d* of cell *i*, whereas the denominator is the sum of all the values of specific GI functions associated with all the grids. G_i* can be standardized as follows:

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{\mathrm{Var}(G_i^*)}} \tag{2}$$

Here, E (G_i^*) and Var (G_i*) are the mathematical expectation and variable coefficient of G_i* respectively. For a grid, a significantly high positive *Z* score indicates that the values of its neighborhood grids are higher than average, with an apparent spatial concentration at a certain distance (Chainey, 2010; Manepalli et al., 2011). A *Z* score near zero refers to spatial dispersion. The hot/cold spots of each GI function can be identified according to the indication of the *Z* score.

3.4.3 Methodology for assessment of ecological connectivity (Paper III)

Inspired by the theoretical research on urban GI mapping and patterns analysis, it is clear that the connectivity principle in GI should be addressed in the process of GI mapping in order to advocate its advantages as a concept for sustainable urban development. In this context, the author studied the GI mapping methods (Wang and Banzhaf, 2018) and decided to undertake GI mapping using the MSPA approach as in-depth case study in the City of Leipzig, Germany (Wang et al., 2019b).

The morphological spatial pattern analysis (MSPA) was first introduced by Matheron (Matheron, 1967) and then enhanced by Soille (2013). It has been further applied in landscape ecology in depth by Vogt et al. since 2006 (Soille and Vogt, 2009; Vogt et al., 2009; Vogt and Riitters, 2017; Vogt et al., 2007). This approach has thus far been applied in order to classify spatial patterns, as well as to map functional networks (Vogt et al., 2009; Wickham et al., 2010) and landscape corridors (Clerici and Vogt, 2013; Vogt et al., 2007). Since 2007, MSPA has continued to be developed for landscape ecological studies. In this paper, I use the latest GuidosToolbox 2.8 to conduct my GI morphological mapping. This toolbox was recently updated by the Joint Research Centre of the European Commission. Preprocessing steps comprise the reclassification of spatial data into a binary map using ArcGIS 10.6, compared to Soille and Vogt (2009) and Wickham et al. (2017), who include GI and built-up structures to match my research focus, namely the spatial patterns of GI.

In order to explore urban GI patterns by applying MSPA (Vogt and Riitters, 2017), I defined the primary green cover types (Davies et al., 2015) that are available from my spatial data source as my foreground (primary targets) map, and I simultaneously set other built-up structures as the background map. From the classified dataset I selected trees, shrubs/young trees, lawn/meadow, agriculture and water as my five focal classes for the mapping of GI morphological patterns, setting all other built-up structures (including railways, paved surfaces, commercial buildings, etc.) to background. These GI categories reflect all primary GI types providing ESS in the City of Leipzig. When carrying out the spatial pattern analysis, I was in line with the methodology by Wickham et al. (2010). Although there was a ready-made MSPA toolbox available, I decided to customize it according to my sophisticated research focus and my much more refined input data. For this reason, I undertook preprocessing steps such as tiling in order to tailor all data for further processing. Preprocessing comprised i) cutting buffered sub tiles; ii) processing buffered sub-tiles for MSPA; iii) resampling the final image to comply with the prerequisites for my MSPA investigation and at the same time support my aim of keeping high resolution dataset at the spatial resolution of 1 meter. If this is not done, there is a risk of losing information due to the change in spatial resolution, because without the aforementioned preprocessing, my input data is restricted to a square map of 10000 * 10000 pixels for MSPA processing (Vogt and

Riitters, 2017). Secondly, I set the connectivity as eight-neighbor in order to analyze each pixel surrounded by different pixels in eight directions, and edge width values of 5, representing the physical distance (width) of 3 meters.

3.5 Case study areas

Both foci on the AMGI and ecological connectivity were explored in one European city, the City of Leipzig, Germany. Leipzig's core urban areas were used to address the GI concept from different angles in Paper II and Paper III.

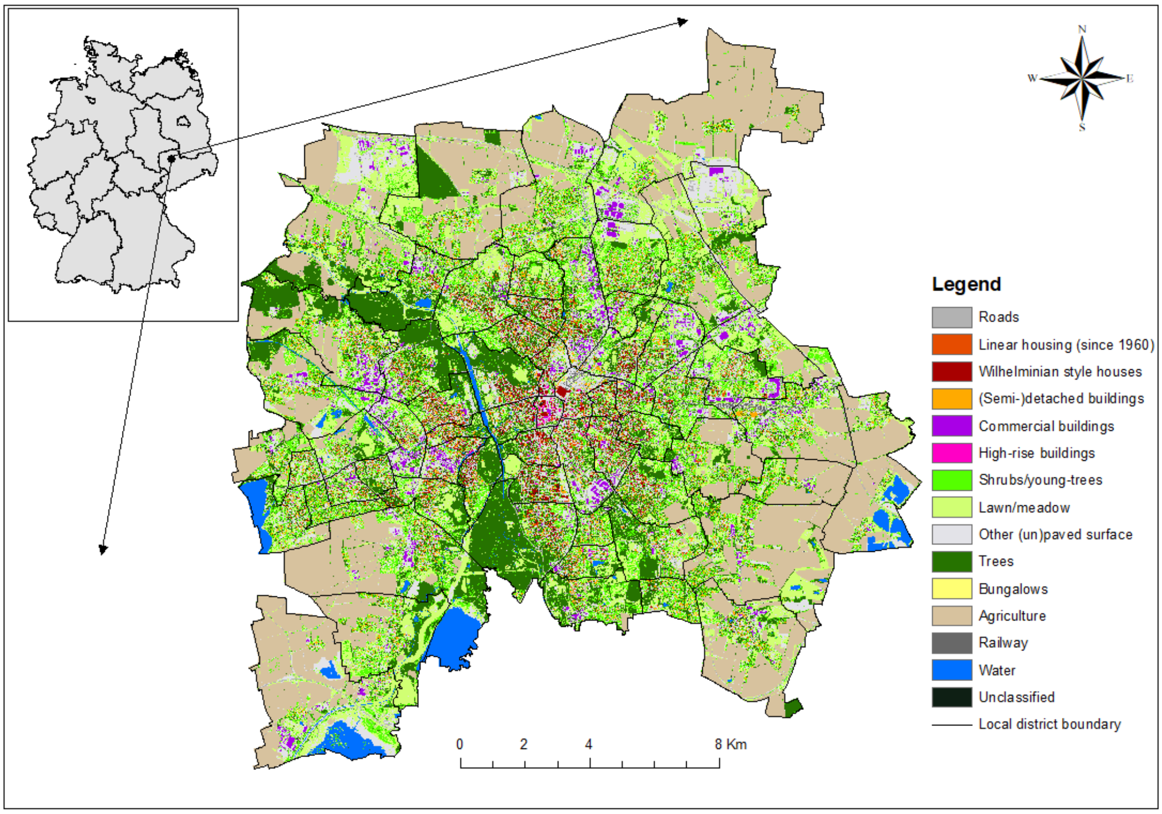


Figure 8. Location and land-use and -cover map of the illustrative case at urban scale, the *City of Leipzig, Germany* (adapted from Wang et al., 2019a)

3.5.1 Urban areas within the City of Leipzig for multifunctional assessment (Paper II)

The research area of **Paper II** is the urban areas of the City of Leipzig, Germany, as shown in Figure 8. My study site is Leipzig, Germany, which covers an area of 298 km², is home to 596,517 inhabitants in 2018 (Stadt Leipzig, 2012) and is characterized by a multitude of high-density built-up areas. Over the past five years, Leipzig has been the fastest growing city in Germany, signifying high pressure on urban GI through housing development and the need for more public infrastructure. Physiographically, the city has one of the most extensive alluvial forests in Europe (Wang et al., 2019b). When further depicting the local GI, we see that it is furnished by long-term urban community gardens and allotments, and demonstrates one of the highest spatial expansions in Germany. Both of these should be reflected in the AMGI.

3.5.2 Sample sites for morphological spatial pattern analysis (Paper III)

In **Paper III**, typical sample sites were selected as areas of interest. My study deals with the city of Leipzig, Germany. Leipzig is located in the north-western part of Saxony and covers an area of 297 km². With 596,517 inhabitants in 2018, it is the largest city in Saxony, with a population density of 2008 inhabitants per km². One of the most well-preserved alluvial forests in Europe traverses Leipzig. From south to north and then towards the north-west, the forest stretches through the urbanized area, serving as the green lung of the city. This is the main reason why it is one of Germany's greenest cities, with an average of 254 m² vegetation cover per inhabitant (Maes et al. 2019; Stadt Leipzig, 2003; 2018). Another notable phenomenon of GI is the high proportion of public community garden allotments (approx. 1,240 hectares) (Stadt Leipzig online, 2018), which provides additional recreational space for thousands of residents (Cabral et al., 2017a) and has a positive influence on the local climate (Cabral et al., 2017b).

During the past decade, Leipzig has become the fastest growing city in Germany, with a considerable increase in economic and cultural diversity. Furthermore, Leipzig prides itself on its enthusiasm for sustainable urban development (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), 2007; Stadt Leipzig, 2019). As part of these efforts, there are major endeavors within urban planning to re-densify the municipal space, thus preventing urban sprawl. As a consequence, land development processes have been leading to competition between GI and housing, including public infrastructure. Building on its good reputation for maintaining and even enhancing urban ecosystems and their services by fostering local GI, the city council has developed a GI quality concept, the so-called Masterplan Green Leipzig 2030 (Stadt Leipzig, 2018). Nonetheless, increasing population numbers and density provoke high leverage. The need to provide schools, kindergartens, local amenities and new dwellings for residents is a strong driving force, shaping the character of urban compaction. To maintain a green city that provides a high environmental quality of urban life, and to offer housing and public infrastructure, is a major current challenge for urban planning. The creation of a new urban development concept for Leipzig is on its way (integrated urban development concept (INSEK) Leipzig 2030; Stadt Leipzig, 2018), which will draw on information such as is generated by this study.

The structure of the built-up area in Leipzig is characterized by three major types of residential buildings: perimeter blocks (Wilhelminian-style buildings) with 5-6 story high buildings in block alignment with interior courtyards, linear multi-story housing (mainly prefabricated slab buildings) of mostly 6-16 story high buildings with common spaces in between, and 1-2 story, (semi-)detached houses (single and duplex houses) with gardens. Being a fairly homogeneous city, many of the 63 local districts can be assigned to one of these dominant types. The city has one of the highest proportions of Wilhelminian-style residential buildings (Gründerzeitbebauung) in Germany. Construction of these buildings began during the reign of King Wilhelm II after 1850 and continued until 1914. Much later, during the era of the German Democratic Republic, one of the country's largest prefabricated slab building complexes was built in Leipzig. It became home to more than 80,000 residents in the 1980s (Banzhaf et al., 2018). Single and semi-detached (or duplex) family houses sprang up in the 20th century in large designated settlement areas and continue to be constructed to date, nowadays rather patchy and dispersed throughout the city.

The customized method (in Section 3.4) is employed for selected sample districts (illustrated in Figure 9), which were considered fairly representative of the three residential types. For reasons of even urban coverage, we selected three sample districts for each: typical local districts for the Wilhelminian style perimeter blocks are Gohlis-Mitte in the north, Neustadt-Neuschönefeld in the central east, and Südvorstadt in the south, constructed during the first period of spatial expansion (mainly around the turn of the 19th century). Linear multi-story housing estates are rather large and located towards the fringe of the urban area. As Grünau was one of the largest linear housing estates in the former German Democratic Republic (Vogdrup-Schmidt et al.), being constructed in the 1970s and 80s, we chose two local districts from this vast area in the southwestern part of the city (Grünau Mitte and Grünau Nord), and Paunsdorf as the third sample district in the eastern part. With respect to the typical urban structure of (semi-)detached houses, we decided to exclude the most recent areas under development due to patchiness and present lack of GI. Instead, we chose three residential areas that were built between the 1920s and 1930s: Grünau-Siedlung in the west, Marienbrunn in the central south and Meusdorf on the southeastern outskirts of Leipzig.

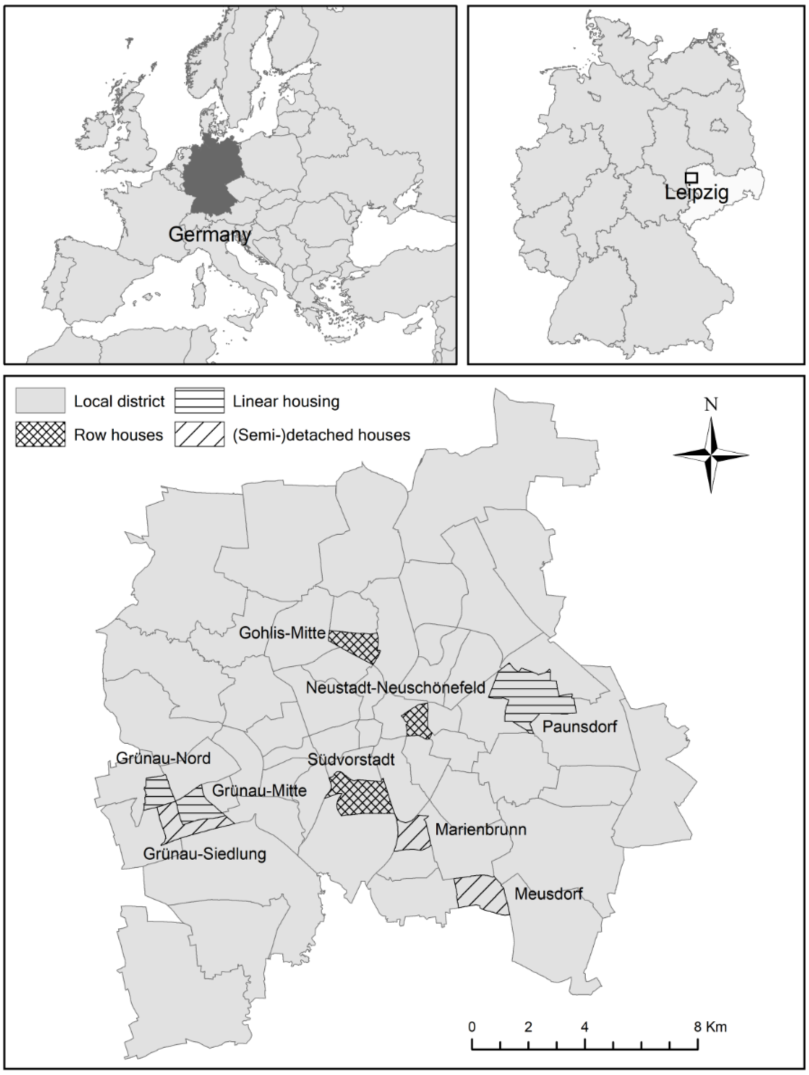


Figure 9. Sample sites of typical residential areas in Leipzig (adapted from Wang et al., 2019a)

SYNTHESIS OF RESULTS

"Sustainable development means improving the quality of life while living within the carrying capacity of supporting ecosystems."

(World Conservation Union, UN Environment Program and World Wide Fund for Nature)

4 Synthesis of Results

4.1 The conceptual evolution of green infrastructure: from functions to multifunctionality

4.1.1 Key definitions of green infrastructure

In its May 1999 report, "Towards a Sustainable America – Advancing Prosperity, Opportunity and a Healthy Environment for the 21st Century", the US President's Council on Sustainable Development initiated efforts to identify and apply concepts of GI to the goal of future sustainable development. Following on from this, The Conservation Fund defined GI as America's natural life support system (The Conservation Fund 2004). In a recent European Commission communication, GI was defined as a "*strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services*" (European Commission, 2012, 2013). Regardless of whether the definitions of GI stem from the US or the EU, they consistently contain natural and human-made components as fundamental elements. Nonetheless, there is no single, widely recognized definition of GI in the literature reviewed to date.

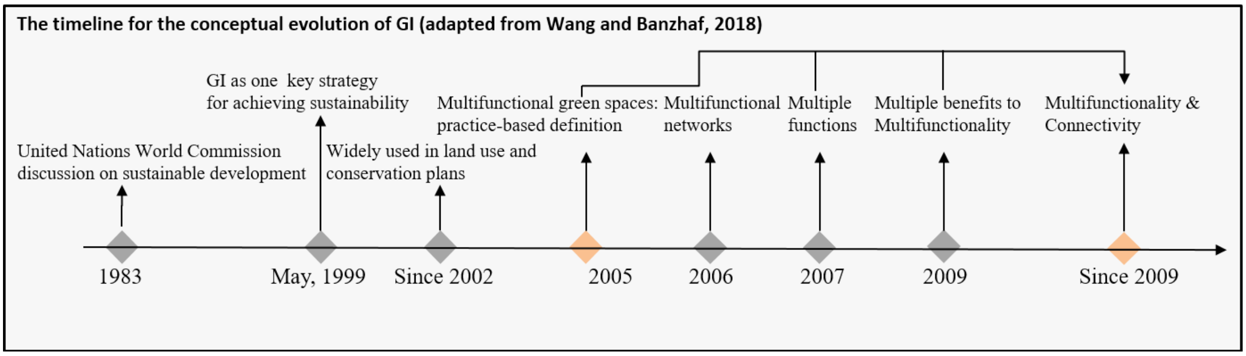


Figure 10. Timeline for the conceptual evolution of green infrastructure (milestones marked with larger, darker icons), adapted from Wang and Banzhaf (2018)

In general, the issue of how to define GI is the first one mentioned in both academic articles and planning guidance. Definitions are therefore a useful starting point for analysis, carrying significant authority and to some degree expressing the values that are attached to the concept (Wright, 2011). In the Technical Report on GI and Territorial Cohesion, it is suggested that GI has been adopted by various design, conservation and planning-related disciplines (European Environment Agency (EEA), 2011). However, this does not mean that GI can be used without a specific definition. Indeed, research on GI might even be hindered by those broad definitions (Van der Windt and Swart, 2008). Based on articles that present lists of GI definitions previously used by several institutions and publications (e.g. Sylwester, 2009; Kambites, 2006; EEA, 2011), I provide a detailed overview of existing key GI definitions (Table A1), constructed on the basis of an analysis of their key points, primary objectives and positions within the development of the GI concept since it was first put forward.

Based on the information contained in Table A4, we present the timeline of GI conceptual development and its specific developmental points in Figure 10. Both of these provide insight into the concept's evolution and developmental trends.

4.1.2 The conceptual evolution of the green infrastructure concept

According to the conceptual evolution of GI (see Figure 10 and Table A3), I identify three mainstream understandings of GI that include their primary translation processes:

1) Translation of the relationship between natural and social systems: bringing nature back into the human community in order to realize a balance between eco-centric and anthropocentric approaches (The President's Council on Sustainable Development, 1999; Benedict and McMahon, 2002).

2) Translation of the former GI advocacy approach into further research that asks 'To what extent can GI work as a practical measure?' This question draws attention to the challenge that persists in terms of how this process might be carried out. When linking theory and policy in order to push GI to the forefront of policy, an example of best practice can be found in England. There, it took just two years for GI to progress from a reference in planning policy (DCLG, 2008) to the basis of emerging national policy (East Midlands Regional Development Agency, 2005; Kambites and Owen, 2006; DCLG, 2008, 2010, etc.). This kind of semantic translation usually becomes an arena of political contestation over how the concept is operationalized (TEP 2005, 2008).

3) Translation of the definition of GI and GI research into an understanding of its multifunctionality. This aspect is attracting increasing attention, even though various definitions have been developed and used in land-use and conservation plans. In this case, the focus is on establishing multifunctional networks, multiple functions, multiple benefits, etc. by enhancing GI and implementing its multifunctional properties. It may stem from the fact that multifunctionality, i.e. the ability to provide several functions and benefits on the same spatial scale, is one key attraction of GI (EC, 2012; EEA, 2014). I find significant evidence of this trend in the 47 articles, located via a specific literature search in the ISI Web of Science and Scopus, that identify studies of multifunctional GI, 60% of which (28/47) were published as recently as 2016. One article notes that the elements of connectivity and multifunctionality make GI an important aspect in landscape planning and management (Landscape Institution, 2009). There seems, therefore, to be an increasing need to address the multifunctional aspect of GI.

In summary, the key definitions and the conceptual evolution of GI analyzed above incorporate three main trends of research aimed at achieving a better understanding of GI, along with three primary translation processes. Despite the intrinsic complexity of the definition of GI (Table. A4), stakeholders are able to understand the significance of GI as such (Wang and Banzhaf, 2018). When applying specific GI to planning, the concept of multifunctionality is more tangible than "sustainability", even though both share the objective of creating more resilient cities.

4.1.3 Multifunctionality in urban green infrastructure as a solution

As urban GI planning has been widely promoted and exploited globally, the initial results of the research for this thesis contribute to the conceptual development of GI. These results suggest the following conclusions:

In order to gain a better understanding of the multifunctionality of GI, the following two dimensions should be included: 1) the functions of GI at multiple scales and their respective roles, and 2) the different functions of GI properties performed simultaneously in addition to their obvious primary functions. Rather than serving just one purpose, such as space for recreation, GI can additionally provide thermo-regulation, water retention, habitat for wildlife and space for recreation.

One key objective of GI planning should be to perform as many functions as possible in a given setting (Wang and Banzhaf, 2018). In another words, limited or single functionality is appropriate only if there is an overriding function that must be safeguarded because of legislation or strategic significance. Street trees, for example, add aesthetic quality to an urban area but also reduce airborne pollution, mitigate wind turbulence, provide shade, and may even increase biodiversity. At this point, these functions can be explained by their long-term, structural and connective character across all ESS. Therefore, the two dimensions of GI multifunctionality should be addressed when selecting the respective indicators for GI assessment. In addition, a robust multidisciplinary approach involving multiple aspects of GI functions should address not only the individual benefits of each function but also their spatial interactions.

Of the six papers in the ISI Web of Science specifically dealing with multifunctional GI assessment, only one emphasizes the importance of multifunctionality in urban GI. However, even this one puts forward only two indicators (i.e. local temperature regulation and population proximity to public green spaces), even though it eventually provides the crucial conclusion that a shift from generic assumptions to local assessment may help understand and analyze GI evolution (Madureira and Andresen, 2014). Although this study provides a localized sample in multifunctional GI analysis, it obviously fails to undertake a more synthetic assessment, since it does not consider some other essential functions of GI (such as recreation or sense of place or enhanced biodiversity). Urban GI is multifunctional in that it addresses geologic, hydrologic, biotic, circulatory, social and metabolic systems, as well stimulates economic development (Herzog, 2016).

4.2 Approaches for the mapping of urban green infrastructure and analysis of its functions

4.2.1 Green infrastructure mapping approaches

Table A. 6 summarizes the results from all the relevant articles selected using the methods from Section 3.2, and the calculated fraction of the quantitative use of each mapping approach. Furthermore, my results show that GI mapping methods which use GIS and integrated modeling tools are the most widely used approaches (56.72%). With reference to GI using integrated GIS tools (Table A6), I chose typology mapping in the North West Regional Spatial Strategy in England (NWRSS) as an in-depth case analysis and as a typical GI mapping approach. The current NWRSS approach has not attempted to make a link between GI classes and the functions/benefits of GI (EEA, 2011; Mazza L. et al., 2011). Likewise, the Liverpool City Region GI Framework and GI Strategy identifies benefits that result directly from particular functions, ignoring benefits that only result indirectly from particular functions via a longer chain (Natural England, 2009).

As a promising result, one type of functional mapping is highlighted as a way of providing an insight into GI: morphological spatial pattern analysis (MSPA), which accounts for about 6% in this review (see Table A.6). It is based on mathematical morphology (Soille, 2003) and identifies hubs and links from a single land-cover map rather than overlaying several maps in a GIS. In doing so, it distinguishes structure from the spatial relationships existing among different land-cover features (Wickham et al., 2010; Ramos-Gonzalez, 2014). In the national assessment of GI research by Wickham et al. (2010), for example, MSPA is highly advantageous because it explores GI configuration and structural connectivity by extending the geographic scope and incorporating land-cover change information. As part of this information, GI mapping using MSPA can be applied in guiding conservation and restoration decisions (e.g. loss of bridges signifies lost connectivity, which can potentially be used to prioritize restoration).

With respect to an integrated GIS methodology, which involves overlaying information, when combined with the principle of horizontal analysis of ecological processes, it has the potential to guide and inform the application of GI mapping at a range of scales and in diverse contexts (Table A.6). As mentioned in the key concern b) above, six scales were identified in the literature reviewed: continental, international, national, sub-regional, urban and local scales. About 42% of the studies not only targeted but also conducted their GI mapping at the sub-regional scale, which includes sub-regions such as the area around Chesapeake Bay, U.S. and some others that may even cross national borders, e.g. Hungary and Austria, Germany and Czech Republic, Spain and Portugal. At sub-regional scale, these broad approaches usually identify land-cover types favorable to nature (e.g. green urban areas, agricultural systems with pastures and mosaics of parcels, forests and other semi-natural or natural dry lands, wetlands and water bodies) that provide a link between high-quality nature areas (Natura 2000, EEA, 2011). About 33% of the studies were conducted at the urban scale.

4.2.2 The pros and cons of main green infrastructure mapping tools

I observed an increase in GI mapping at the urban scale since 2014. This might be due to the Urban Atlas, which contains a high spatial resolution land-use database for the years 2006 and 2012 that is readily available in Europe (European Environment Agency (EEA), 2011). At the pan-European scale, 6% of the articles dealt with the regulation of water flows and temperature control (Mubareka et al., 2013; Snall et al., 2016; Liquete et al., 2015). Gill et al. (2008) suggest that more attempts should be made to link GI categories to the potential benefits and functions provided. In a review of all the literature, there were only three publications (Barredo et al., 2016; Weber et al., 2006; Wickham et al., 2010) that demonstrated accuracy and precision in their mapping approaches, and more than two thirds of the articles did not address the question of rigor at all.

For the mainstreaming GI mapping tools (in Table 3), I analyzed mainly the advantages and disadvantages of methods such as the Life Cycle Assessment (LCA), the Multifunctional Landscape Assessment Tool and the Urban Forest Effects Model (UFORE), as shown in Table 3.

Table 3. Critical review of selected GI mapping tools (adapted and cited from Tzoulas et al., 2007; Wang and Banzhaf, 2018)

Tools name	Methodology	Key purpose	Contributions to early stages of GI planning	Limitations
Life Cycle Assessment (LCA)	Accounts for a broad range of categories such as water, energy use, greenhouse effect, toxicity, resource extraction, and land use based on international standards.	Evaluate or compare the environmental impact of distinct green spaces (e.g. energy and material input and output).	Carbon Footprint analysis; Farm Carbon Assessment Tool; Climate Leadership in Parks	Generally, lacking in consideration of cultural values and social justice issues, although some attempts have been made to include these dimensions as an aspect of LCA in an effort to better align with sustainability goals.
Multifunctional Landscape Assessment Tool	The tool generates input data, including the area of each habitat type, its functional attributes, and ratings of each attribute based on user perception and expert assessment depending on the site-specific context.	Evaluate the design of agro-ecosystems.	Help landowners and planners make informed decisions about land use that take into consideration the multifunctionality of the current system and potential future functions.	Limited in its ability to capture multiple spatial and temporal scales simultaneously, though the assessment may demonstrate differences in time and space dimensions.
Urban Forest Effects Model (UFORE)	The assessment of urban forest structure is conducted through aerial and ground-based measurements to determine area of tree cover, number of trees, species composition, tree biomass, and other relevant factors	Assess forest structure and functions. Also used to plan tree establishment to support desired functions	Help in calculating functions provided by local urban forests, such as air pollution removal, carbon sequestration, volatile organic compounds emissions, and energy conservation for nearby buildings.	Designed for woody plant cover, so it does not account for other types of vegetation and cover, and focuses heavily on ecological functions, mostly neglecting cultural and production functions

4.2.3 Analysis of the functions of urban green infrastructure

According to the results shown in Figure 11, the GI functional analysis is still lacking in 40% of all the reviewed literature (n=67). About 60% of the articles analyzed looked at different GI functions, such as regulation of water flows (11%), temperature control (9%), accessibility for exercise and amenity (7%) and recreation (7%). GI functional analysis can also be described in terms of two main GI roles: 1) improving ecosystem functioning and promoting ecosystem services; 2) promoting societal well-being and health. The other two roles addressing the multifunctionality of GI are comparatively weak (European Commission, 2012), namely, 3) protecting ecosystems state and biodiversity, and 4) supporting the development of a green economy and sustainable land and water management. Further studies would be required to identify how multiple functions fit into these four roles of GI on the same piece of land. In terms of future research, a comprehensive view of GI is required; it should focus on its multifunctionality at different scales.

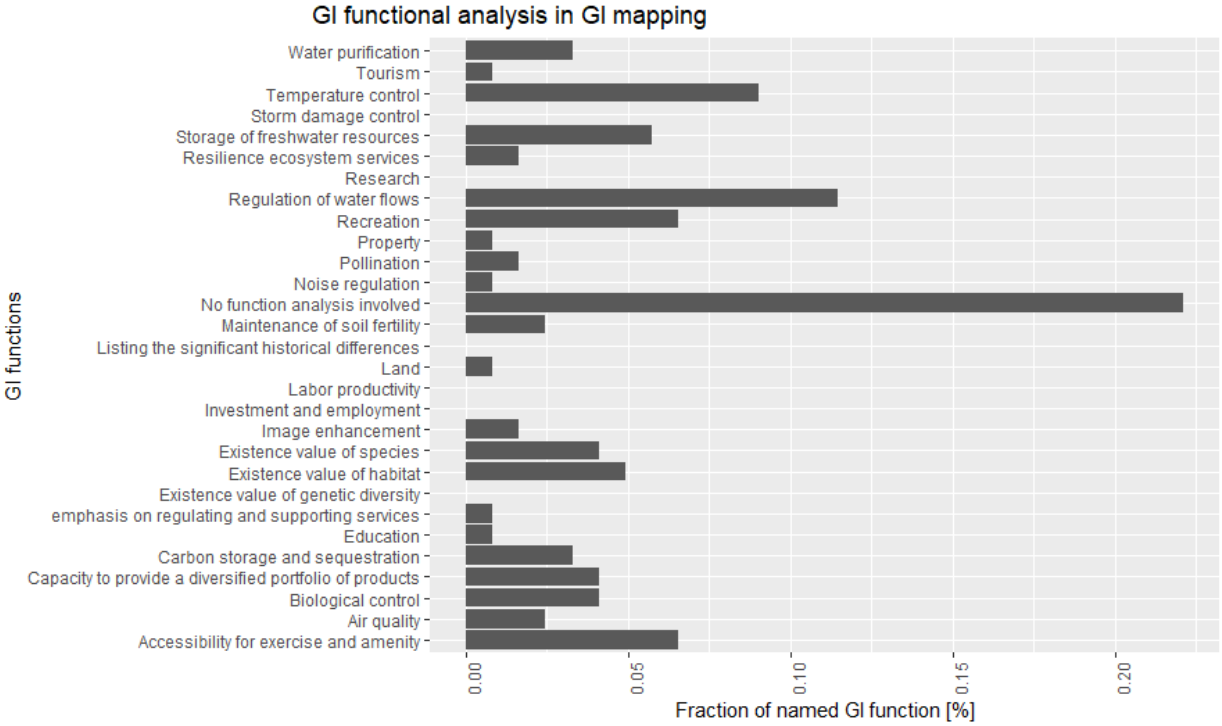


Figure 11. GI functional analysis in GI mapping (adapted from Wang and Banzhaf, 2018)

4.3 From gray to green: a comprehensive typology of urban green infrastructure

Urban planning, whether for land-use or landscape management purposes, can be organized well only if a comprehensive typology or an integrated overview of the whole ecosystem is available. To make up for the absence of an urban GI typology, I presented an integrative GI typology, adapted from the urban GI Components Inventory stemming from the Green Surge project (Davies et al., 2015; Hansen et al., 2017; Kabisch et al., 2015), as the guiding basis for the AMGI . I updated it based on newly released reports from the Green Surge project, and ordered it by the intensity of human influence/association with GI in Table A5. It is an essential element in a checklist for AMGI, given that the GI types involved (service provision units) should be taken into consideration while conducting GI assessment. An essential aspect in AMGI is that of supporting the core attraction of the concept of GI, i.e. its multifunctionality (Wang and Banzhaf, 2018), taking into account the fact that multiple ESS may be provided by different GI types. The GI typology from the Green Surge project is not only recommended as a predominantly functional classification of urban GI by MAES (2016b) but also recognized as a fundamental element in GI research, making it possible to review the links between GI types and ESS (Pauleit et al., 2019a; Pauleit et al., 2017).

4.4 An integrated indicator framework for assessment of multifunctional green infrastructure

GI should be strategically planned and delivered on a range of scales to provide usable space with support for natural and ecological processes (Grant, 2010). The indicator-based framework proposed in this thesis permits the use of an ES framework to evaluate different types of GI and their functions and benefits. Translating the aggregated effect of ESS into a holistic strategy for urban GI planning is a significant step forward in terms of the value of the concept of GI. However, there are still major challenges as regards the transferability and translation of the whole framework under different location-specific GI planning.

4.4.1 Addressing multi-dimensions of sustainability via urban green infrastructure

In this section, the three aforementioned prominent frameworks I to III are analyzed according to their structures, benefit groups and data availability as well as respective qualitative and quantitative measurements. In so doing, I classify the different indicator frameworks with respect to the four central dimensions. The results for the multidimensional analysis are illustrated for each framework in the respective Appendix tables (A1-A3). Below, I first present my analytical results for each of the frameworks and then provide the synthesis in an integrated framework for AMGI.

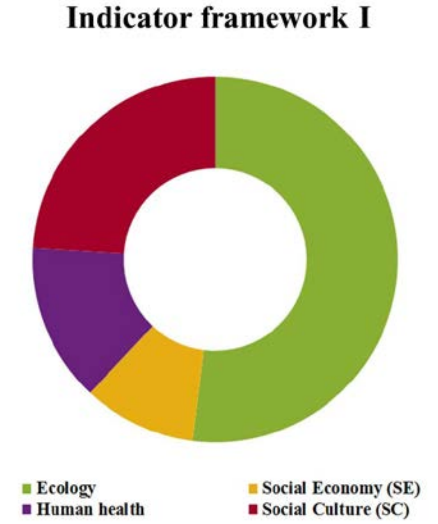


Figure 12. Indicator framework I for ESS assessment, from MAES, classified in terms of four dimensions, i.e. ecological (green), socio-economic (yellow), socio-cultural (purple) and human health dimension (red).

4.4.2 Multidimensional analysis of indicator frameworks I – III towards sustainability

4.4.2.1 Indicator framework I for assessment of ecosystem services

Indicator framework I (Table A.1), from MAES (2016) is composed of 40 indicators. In total, one quarter of the indicators involves more than one dimension. In summary, 52% of the indicators relate to the ecological dimension, 24% of the indicators relate to the socio-cultural dimension, 14% of the indicators refer to human health, and only 10% refer closely to the socio-economic dimension.

4.4.2.2 Indicator framework II for assessment of urban green infrastructure implementation

The framework from the IEEP is composed of 39 indicators, which include not only those ESS provided by GI but also a range of GI benefit groups, e.g. GI benefits for human health and well-being, investment and employment, and so on (Table A.2). As one example, employment resulting from GI initiatives is not an ESS but a benefit provided by GI. **Indicator framework II**, presented in Table A.2 in terms of the four dimensions of sustainability, has great potential for the AMGI on the grounds that it contains a wide range of GI benefits and comprehensively reflects GI functions. A total of 40% of these indicators are involved in more than one dimension. In summary, 45% of indicators relate to the ecological dimension, 22% relate to health, i.e. human health, 21% relate to the socio-economic dimension, and only 12% closely relate to the socio-cultural dimension.

Figure 13. Multi-dimensions towards sustainability of indicator framework II: ecological, socio-cultural, socio-economic and human health (adapted from Wang et al., 2019a)

Indicator framework II：for GI implementation, from the IEEP, and classified in terms of four dimensions, i.e. ecological dimension (green), socio-economic dimension (yellow), socio-cultural dimension (purple) and human health dimension (red), adapted from the source at http://ec.europa.eu/environment/nature/ecosystems/studies.htm#implementation).

4.4.2.3 Indicator framework III for assessment of the contribution to a green economy

In Table A.3, there are 37 indicators for GI valuation derived primarily from the indicator framework GI Valuation Toolkit (West, 2011). The analysis of **indicator framework III** from the EMDA, shows that 68% of all indicators belong to more than one dimension of urban sustainability. That is to say, compared to **indicator framework I and II**, it has the highest percentage of indicators addressing multi-dimensions of sustainability. In detail, 35% of indicators relate to the socio-economic dimension, 29% relate to the ecological dimension, 20% relate to human health and 17% closely relate to the socio-cultural dimension.

Indicator framework III supports a shift towards a green economy, from the EMDA, classified in terms of four dimensions, i.e. ecological dimension (green), socio-economic dimension (yellow), socio-cultural dimension (purple) and human health dimension (red).

Figure 14. Multi-dimensions towards sustainability of indicator framework III: ecological, socio-cultural, socio-economic and human health dimensions (adapted from Wang et al., 2019a)

4.4.3 Integrated indicator framework for assessment of multifunctional green infrastructure

The three selected indicator frameworks are compared in order to analyze their potential coverage of the four sustainability dimensions as well as further relevant characteristics for the assessment of multifunctional GI. Figures 13 to 15 depict their share of multiple dimensions for sustainable urban development. **Indicator framework I** clearly emphasizes the ecological dimension, while **indicator framework II** is relatively weak with regard to the socio-cultural dimension but covers the dimension of human health and well-being. **Indicator framework III** strongly supports the socio-economic dimension of GI. It may therefore be concluded that the three indicator frameworks contribute in specific ways to a more integrative indicator framework for AMGI, while also demonstrating limitations.

As one important conclusion, these three frameworks are complementary within their special focus on various scales and dimensions. I therefore make full use of their contributions and adapt their dimensions and aspects to an integrated indicator framework, which is a *multi-scale* and *multidimensional* indicator database (Table A1 to A3). This synopsis enables the integration of their beneficial contributions into just ***one*** framework as an indicator pool for undertaking an AMGI.

The comparative results of the relevant spatial extents, the percentages of supply/demand indicators (see the Fig. S2 in Paper II) from indicator framework I to III, as well as the respective information (Text S1 in Paper II) are provided in the supplementary materials (in Paper II) in order to facilitate the potential application of the methodology developed. This approach is sensitive to criteria such as spatial scales and data availability, and is therefore not applicable to all situations. However, it is the first time that such an explicit indicator framework has been proposed for AMGI, while including multidimensional analysis for sustainability. This result helps ensure the constancy of GI assessment as well as combine and scale up the research on AMGI. A major restriction in terms of the potential application of my integrated framework is data availability in certain cultural contexts.

In terms of synoptic findings, I concluded that there is potential to conduct AMGI at multiple scales, but substantial data gaps must be filled before a fully integrated and complete GI assessment can be carried out. In conclusion, applied studies at multiple scales are needed to manifest the usefulness of my AMGI framework as well as reinforce it in practice.

4.5 Exemplification of an assessment of multifunctional green infrastructure

In this section, an illustrative case of AMGI at urban scale (Wang et al., 2019a) is presented in order to validate the methodology developed in Section 3.4.2.

- **Stage 1: The need to address multifunctionality and multi-dimensions of sustainability.**

As a pre-evaluation, some background information on my study area is necessary in order to facilitate the work flow from stage 1 to 3, depicted in Figure 8. The study site is Leipzig, Germany, which covers an area of 298km², is home to 596,517 inhabitants in 2018 (Stadt Leipzig, 2012) and is characterized by a multitude of high-density built-up areas (Figure 8). In the last five years, Leipzig has been the fastest growing city in Germany, resulting in high pressure on urban GI through housing development and the need for more public infrastructure. Physiographically, the city has one of the most extensive alluvial forests in Europe. When further depicting the local GI, it is furnished by long-term urban community gardens and allotments, and demonstrates one of the highest spatial expansions in Germany. Both of these should be reflected in the AMGI. For my priority setting, my intention is to address the ten GI benefits in terms of how best to use the approach developed. In addition to considerations of data availability, my principle provides at least one example for each of the GI benefits in order to illustrate the usage of the proposed framework and provide some methodological guidelines.

- **Stage 2: Contextual assessment in the City of Leipzig, Germany**

The assessment is conducted in Leipzig on the basis of preprocessing in Stage 1. I set my focus on the urban scale (Figure 15), and concentrate primarily on the capacity of GI benefits. The selected indicators and analysis can be found in Table 2. Indicators that are not available in the study area are marked as N/A, and I highlight potential methods and references respectively. For example, indicators such as No. 00029 (number of visitors to protected sites per year) and No. 00030 (number of local users for hiking, camping, nature walks and jogging), etc. are not available at the whole urban scale, however, I itemize newly developed methods e.g. smartphone apps such as MapNat app (Priess et al., 2014).

The contextual assessment leads to a lean indicator framework as shown in Table A.7, guided by my workflow. The selected indicators are defined in Figure 15, evaluated either quantitatively as measurements or qualitatively by consulting local study sources.

With regard to contextual assessment, we summarized the evaluation results of GI benefits for the whole urban area (see Table A6), which are aggregated to the urban scale. I can conclude that GI provides natural resources such as carbon storage 11.8 MgC/ha on average (Schröder et al., 2013; Strohbach and Haase, 2012), and water surfaces account for 2.5% of the whole municipal space. GI function can be reflected from around 13 ha (0.04%) wetlands and 41 ha (0.14%) vegetation alongside water bodies to regulate surface run-off water. They are identified and mapped as river-related GI in order to indicate the GI capacity of water regulation.

In terms of multifunctioning GI, there are several GI elements worth highlighting in Leipzig. For example, there are around 28.2 m^2 allotments and community gardens per inhabitant. These are not only for food self-supply but also contribute significantly to the formation of recreational spaces. Both of them are evaluated and reflected in Figure 16. In total, there are around 70 m^2 recreational spaces for each inhabitant, encompassing gardens, parks, urban forests, allotments, sports and leisure facilities, zoological and botanical gardens, and so forth, which are widely dispersed across the city. Another multifunctional GI is dedicated to the urban alluvial forests (see Figure 8), in total 1,033 ha in Leipzig. These are not only recreational areas for urban dwellers; in addition, they have special value for habitat, species and genetic diversity. In this case, they can be marked as having a specific conservation function (i.e. neither associated with the actual use of ecosystems nor with their potential use in the future) for sustainable development and future generations (East Midlands Development Agency (EMDA), 2010). Their existence ought to be protected, for conservation is their primary function (see Figure 16).

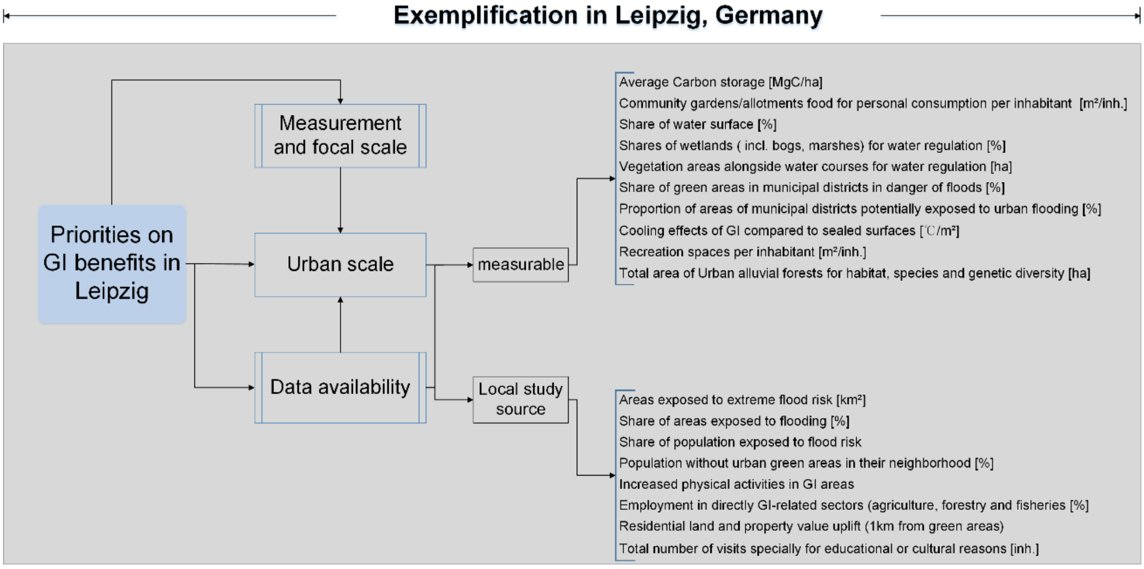


Figure 15. Results from indicator selections for the illustrative case in Leipzig, Germany (adapted from Wang et al., 2019a)

Regarding resilience against exposure to urban flooding, we find a proportion of 57% of green spaces in local districts exposed to flooding. This is of particular concern where rivers are running adjacent to built-up areas, of which Leipzig possesses a multitude, such as White Elster, Pleiße, Parthe, Luppe (Stadt Leipzig, 2019). This is reinforced by a local case study by Kubal et al. (2009), which concludes that about 45 km^2 of area, i.e. 15% of the city, is exposed to extreme flood risk. As for the GI function related to local climate change, the urban GI provides nearly 0.25 °C/m^2 of cooling effects (Schwarz et al., 2012), compared to the sealed surfaces. This means that the further the distance to local GI, the larger the exposure to urban heat island effects. To reflect the GI function in support of employment, we find that GI elements such as agriculture, forest and fisheries provide an employment rate of about 13.7% in the study area.

With respect to external benefits due to the development of GI, the increment values of both ground land (Stadt Leipzig Sozialamt, 2016) and apartment rent (Wohnungsbörse Leipzig, 2019) imply a GI function on investment, since we observe an escalate in both with an increasing proximity to GI. Hence, we detect hot spot areas of GI on the recreational function map (Figure 16). In all probability, the ‘good’ (standard ground value from 280 – 400 □/m^2) and ‘super good’ (above 400 □/m^2) lands are situated near the parks and urban alluvial forests. Detailed results are presented in Table 2. GI functions (the above-ground carbon storage, allotments producing food for personal consumption, river-related GI for water regulation, recreation function, and the special conservation benefits of GI for habitat, species and generic diversity) can be further illustrated by calculating the Getis Ord Gi* index (see Section 3). The results calculated serve to identify the spatial patterns of the hot/cold spots of each GI function. Both the hot spots and cold spots of GI functions are allocated all over the city. There are no regular patterns among different functions. The resulting maps show variation in GI functions over space. However, it can be concluded that there is a specific spatial concentration of the recreation function in the central western part of Leipzig, which proves that the multifunctionality of the urban alluvial forest plays a significant role for residents in Leipzig.

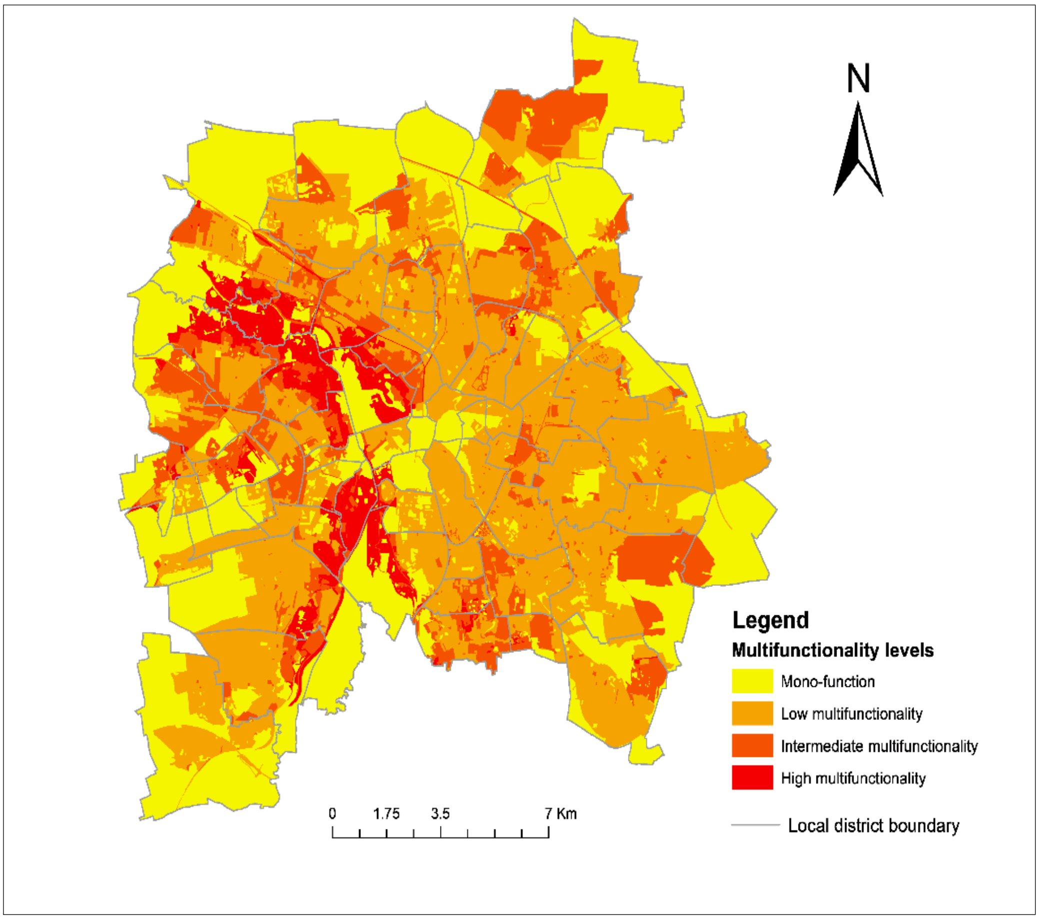


Figure 16. Spatial distribution of GI multifunctionality in Leipzig, Germany (Wang et al., 2019a)

The five GI functions (i.e. carbon storage, allotments for personal consumption, river-related GI for water regulation, recreation and conservation) are overlaid to identify the multifunctionality of GI in this case study. The results show different intensities of multifunctionality: mono-function, low, intermediate and high levels of multifunctionality, as displayed in Figure 16. The spatial distributions of multifunctionality present the complex urban ecosystems of different GI functions in relation to the spatially heterogeneous multifunctional GI. There are no inevitable connections between hot spot areas and multifunctional areas. What is important is that the multifunctional areas generally cross the local district boundaries. From the city center to the outskirts, the level of multifunctionality is diverse and slightly inclined to the mono-function direction that is assigned to agricultural land.

- **Stage 3: Retrospective assessment**

For the retrospective assessment, I re-evaluated my illustrative case according to the guiding questions presented in Section 3 (in the yellow box). The results show that the selected indicators convey four dimensions of urban sustainable development, and their fractions do not show apparent bias: ecology (39%), socio-economy (23%), socio-culture (16%) and human health (23%). However, they do show great restrictions in the socio-economic dimension due to a lack of data availability. Overall, we employ 18 indicators in total, and the GI types encompassed in my AMGI analysis are checked and compared with my comprehensive GI typology adapted from the urban GI Components Inventory of the Green Surge project (Kabisch et al., 2015) and marked as YES/NO in the last column (Table A5).

4.6 Morphological spatial patterns analysis for the City of Leipzig

4.6.1 Spatial patterns analysis

According to my customized method in Section 3.4, my adapted MSPA resulted in seven classes of GI spatial patterns. They are referred to as core, bridge, loop, branch, edge, perforation and islet (Table 6). These classes reflect the spatial heterogeneity of GI in residential areas. Instead of overlaying several maps in geographic information system software, I employed a method from Soille and Vogt (2009) based on concepts from mathematical morphology (Soille, 2003). The MSPA classes are defined in Table 1.

The results of MSPA mapping are shown in Figure 17. For each type of residential area, we see that the major differences are in the GI bridges and loops. Both the bridges and loops of green spaces contain significant ecosystems for the local flora and fauna. As a result, they are recognized as ecological networks and play a significant role in biodiversity and movement paths, not only for the animals but also for the residents.

Table 4. Classification of morphological spatial patterns (Wang et al., 2019b)

MSPA classes	Definitions
Core	GI surrounded by all sides (8-connectivity) by GI and greater than 3 meters distance from built-up areas
Bridge	GI that connects two or more disjunctive areas of GI cores
Loop	GI that connects an area of GI core to itself
Branch	GI that extends from one area of core, but does not connect to another area of core
Perforation	Transition zone between GI and built-up areas for the interior regions of GI; it is in the shape of a doughnut in which a group of GI types are shaped by perforations (inner edges).
Edge	Transition zone between GI and built-up areas
Islet	Unconnected class without core

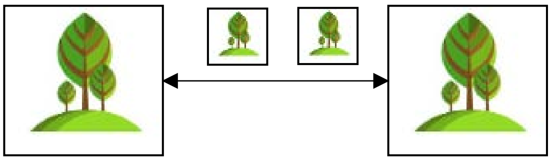
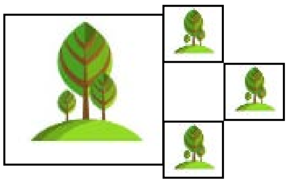
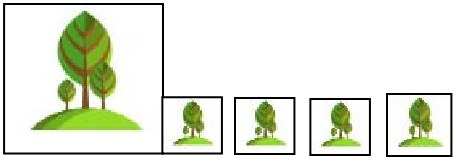
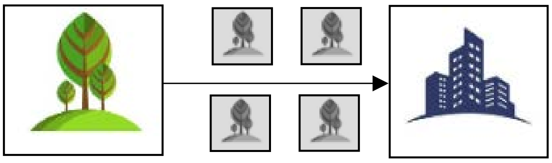
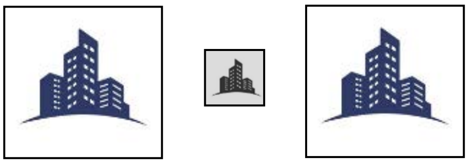
4.6.2 Interpretation of morphological spatial patterns

The MSPA developed here resulted in seven classes with specific geometric features. This prerequisite enabled me to define and analyze my classes in depth in accordance with my research aim and the underlying LULC classes, increasing my understanding of structural connectivity in GI. I characterized each class in Table 1 as different GI patterns in terms of the GI concept by Wang and Banzhaf (2018), and this gave me a better understanding of their relationships in my local sample districts. As Table 2 shows, MSPA classes may either belong to GI exclusively (pure GI patterns) or they may be part of GI connected to built-up areas. The GI classes exclusively encompass GI core, bridge, loop and branch. As for the GI connected to built-up areas, these enclose GI perforation, edge and islet. They all contribute to structural connectivity to different extents. GI core in Table 4 is usually composed of a broad spectrum of types of green and GI elements. Other GI spatial patterns such as bridge, loop, branch etc., however, are connected to GI cores in distinct ways.

Figure 17. GI spatial patterns map in three types of the residential area (Wang et al., 2019a)

Moreover, I also converted MSPA classes into seven different structural classes (in Table 5). These reflect six intensities of structural connectivity: i) external connectivity 1 (GI core areas to other different GI core areas), ii) internal connectivity 1 (GI core areas to the same GI core), iii) partially connected to GI core; iv) internal connectivity 2 (transition zone between GI to built-up areas for interior regions of GI cores), v) external connectivity 2: transition zone between GI and built-up areas, and vi) GI islet that is isolated and unconnected. Meanwhile, GI bridge, branch and loop represent GI structural connectivity. For the MSPA classes from bridge to islet, the morphological connectivity becomes progressively weaker due to the spatial correlations between GI (foreground) and various built-up areas (background). These tend to be influenced by human activities. I could therefore conclude that core areas are currently primary functioning GI and others are classified in terms of their relationships with surrounding GI core. GI bridges which connect to the different GI cores are significant corridors for providing favorable habitat and paths from one core to another. GI loops represent shortcuts connecting spaces of a core area to itself. In general, both the bridges and loops indicate functional pathways, the maintenance of which is crucial in sustaining any transfer of individuals between the same or different GI cores. Branches might be developed from bridges and loops, and further recognition of locations of branches and bridges would then provide insight into where there might be vulnerable GI corridors. Perforations and edges are both transition zones between GI cores and the built-up area.

Table 5. Conversion of MSPA classes into structure classes (adapted from Wang et al., 2019b)

MSPA classes	Structure classes	Illustrations
GI exclusively		
GI core	GI core	
GI bridge	External connectivity 1: GI core areas to other different GI core areas	
GI loop	Internal connectivity 1: GI core areas to the same GI core	
GI branch	Partial (half) connectivity	
GI connected to built-up areas		
GI perforation	Internal connectivity 2: transition zone between GI to built-up areas for interior regions of GI cores.	
GI edge	External connectivity 2: transition zone between GI and built-up areas.	
GI islet	Unconnected	

4.6.3 Ecological networks analysis

In order to explore the similarities and differences of GI spatial patterns in each type of residential area, the GI spatial patterns of all sample local districts were extracted separately. The results for the samples from nine local districts are illustrated according to differentiated types (see Figure 18 to Figure 20). If these three figures are compared, it can be found that a similarity between each residential area in terms of the fractions of varied spatial patterns. Their differences mainly pertain to the proportions of edge and bridge patterns. Both reflect the ecological connectivity of green spaces in morphology. It can thus be concluded that the major difference between each residential area is the spatial connectivity due to different configurations of green spaces. The different configurations of green spaces result in the distinction between ecological networks and affect the ecological connectivity in (semi-)detached houses, linear houses and perimeter blocks too.

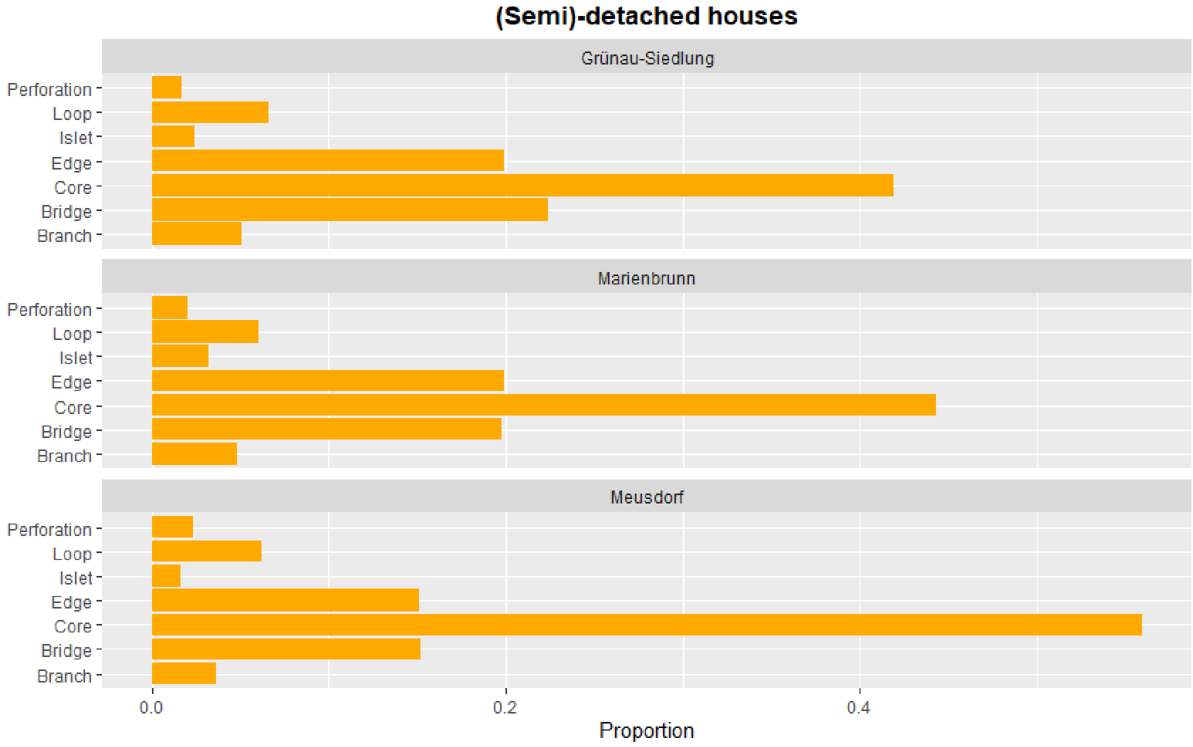


Figure 18. GI morphological spatial patterns in districts dominated by (semi-)detached houses (extracted from Wang et al., 2019b)

Each of the three local districts dominated by (semi-)detached houses (i.e. Grünau-Siedlung, Marienbrunn and Meusdorf) has similar structures/distributions of morphological spatial patterns, as shown in Figure 18. From high to low, the order of proportions of the top five spatial patterns are the same (i.e. GI core > GI bridge > GI edge > GI loop > GI branch). There are relatively high fractions of GI core areas in all three districts, which reflects a relatively high level of pure GI coverage. With respect to the GI bridges and GI edges, these account for almost the same percentage. As a result, the probabilities between external connectivity 1 (GI core areas connected to another different GI core area) and external connectivity 2 (GI cores to built-up areas) were nearly the same. The respective proportions of overall spatial patterns were quite similar from GI core to islet.

As for the local districts with prevailing linear multi-story housing estates (i.e. Grünau-Mitte, Grünau-Nord and Paunsdorf), the results show similarities in the distribution of GI morphological patterns as well (see Figure 19). From high to low, the orders of proportions of the first five spatial patterns are consistent in each, i.e. GI core > GI edge > GI bridge > GI branch > GI loop. For this residential type, it is interesting to note that the proportions of GI bridge are almost half of the GI edge patterns which connect to other built-up areas. This result explains that GI in districts dominated by linear multi-story housing frequently extends right up to typical building structures rather than to other GI cores.

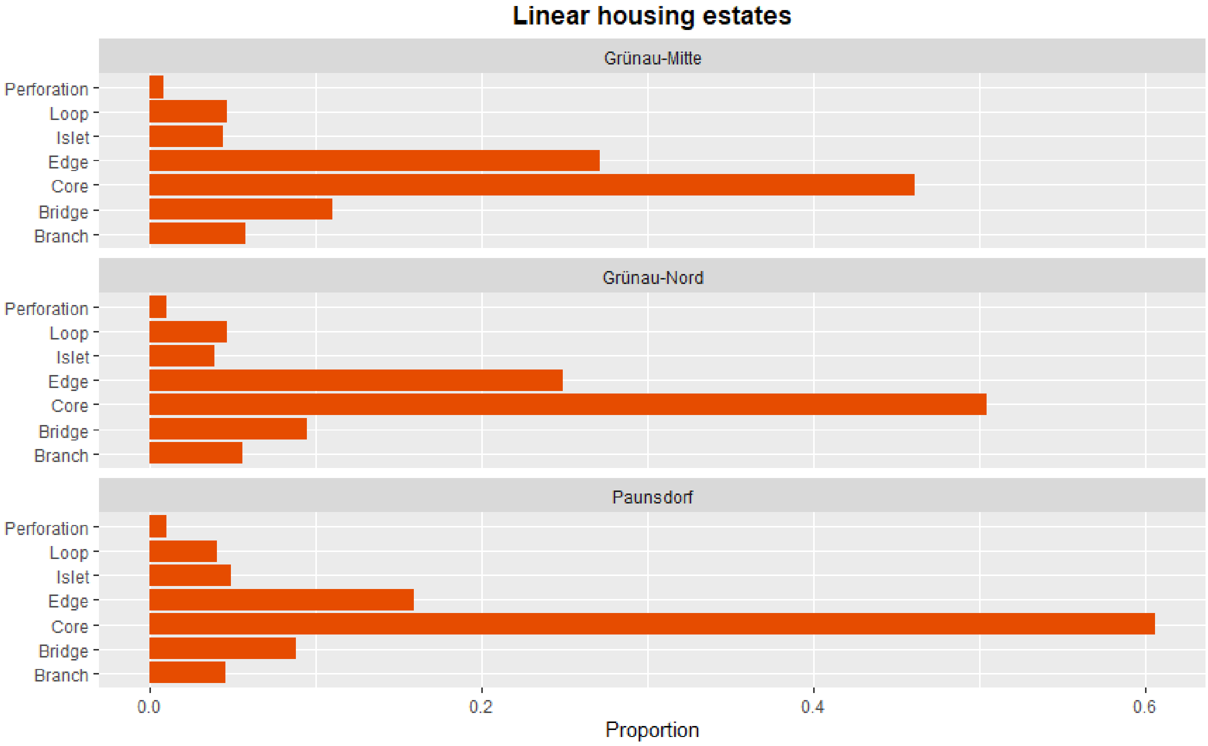


Figure 19. GI morphological spatial patterns in districts dominated by linear housing estates (extracted from Wang et al., 2019b)

It reveals the potential limits of GI connectivity in these sample districts (linear housing estates), for the reason that GI edges (external connectivity 2) have less structural connectivity in comparison with GI bridges (external connectivity 1), according to Table 5.

For those local districts dominated by perimeter blocks which contain mostly Wilhelminian-style buildings, i.e. the typical residential districts of Gohlis-Mitte, Neustadt-Neuschönefeld and Südvorstadt in Figure 20, it is notable that the fractions of GI cores and GI islets are the highest in comparison with the aforementioned two sample districts (i.e. semi-detached houses and linear houses). However, compared to the districts dominated by linear multi-story housing types (in Figure 19), the GI bridges apparently represent much less than half of GI edge patterns. During the era of urban expansion there was extremely high pressure on urban dwellings due to the strong growth of cities undergoing industrialization (mainly during the second half of the 19th century). Therefore, two contrasting urban structures were created that still dominate the urban character of Leipzig: Wilhelminian-style perimeter blocks in block alignment, some of them with interior courtyards, but hardly any GI in the streets, and few large areas with allotment gardens that met the dwellers' need for green spaces. As one significant result from the MSPA shows, each of the three typical residential areas has its own spatial GI patterns, whereas within the same type of residential district the GI patterns are similar.

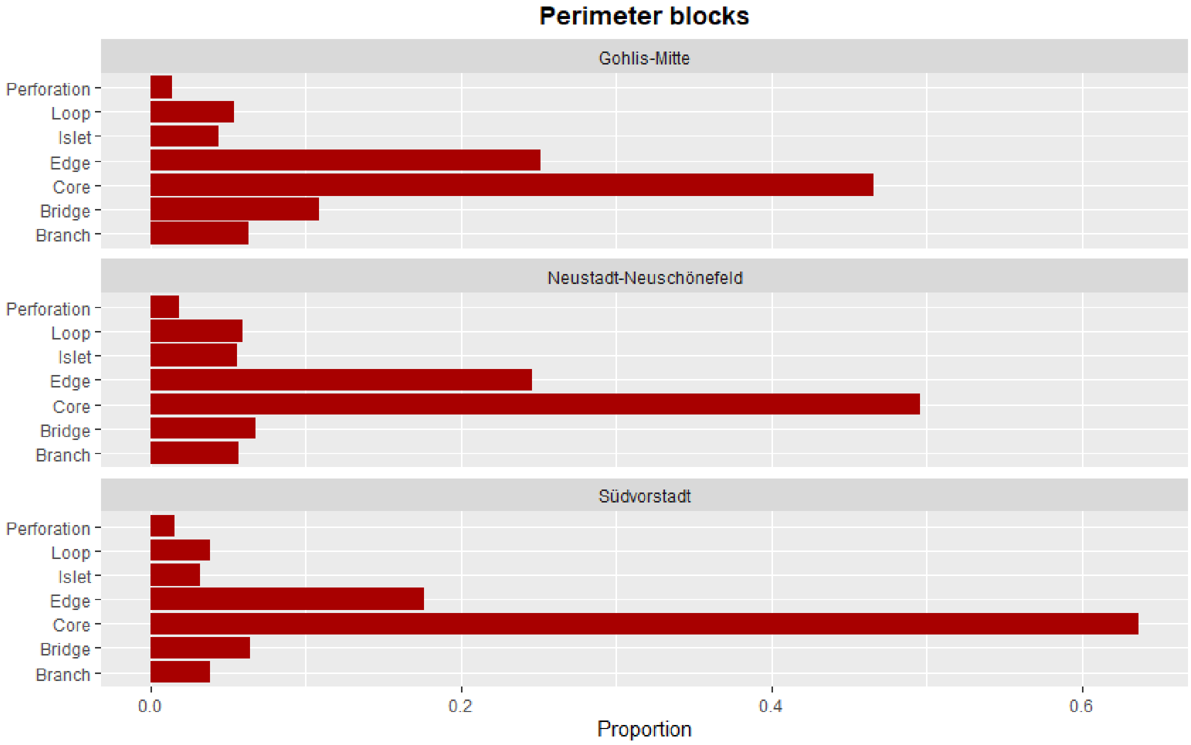


Figure 20. GI morphological spatial patterns in districts dominated by perimeter blocks (mostly Wilhelminian-style buildings from 1850 to 1914, extracted from Wang et al., 2019b)

4.6.4 Gini coefficient analysis

Equity forms a link between social and environmental sustainability (European Commission, 1996). It is thus important to know the levels of equity in order to enhance sustainability between society and environment. In order to establish the spatial equity of GI distributions, the GI-adapted Gini coefficient index is calculated and presented in Figure 21 and Table 6.

In the nine sample local districts explored in Table 6, the Gini coefficient ranges from 0.14 to 0.87 and shows great differences, although the gaps amongst the same type are restricted. For each type of residential area, i.e. (semi-)detached houses, linear housing estates and perimeter blocks, the Gini coefficient ranges from 0.096 to 0.463, representing large differences in GI distribution, from even to comparatively uneven, as the smaller Gini coefficient indicates a higher equity of potential access to the same amount of GI and vice versa.

In addition, the overall Gini coefficient of each exemplified residential district was also evaluated to reflect the GI equity status (from even to uneven). As Figure 21 shows, the spatial equity of GI distribution varies depending on the existing type of residential area. Despite small variations in the Gini coefficient among different local districts, the GI coefficient tends to increase strikingly from samples with (semi-)detached houses to linear multi-story housing districts, demonstrating the highest rates in local districts with perimeter blocks. This means that GI distributions in districts dominated by perimeter blocks are the most unequal, while those local districts with (semi-)detached houses demonstrate the most equal distribution of GI.

Compared to those local districts dominated by linear multi-story housing and perimeter blocks, the GI distributions of local districts with (semi-)detached houses are relatively even. More strikingly, GI availability is most uneven in local districts with perimeter blocks, even though there are interior courtyards in most blocks of these historical building complexes. Consequently, residents in such typical residential districts, e.g. Neustadt-Neuschönefeld, Gohlis-Mitte, or Südvorstadt, probably have the lowest equity in terms of accessing the same amount of GI.

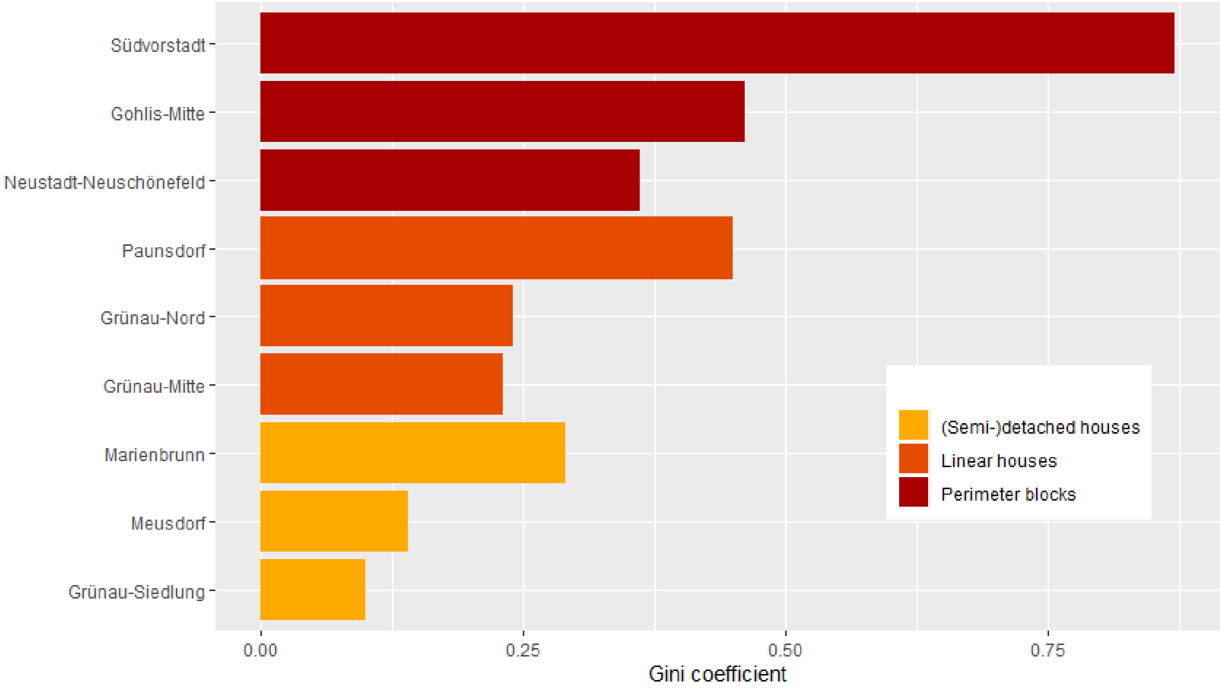


Figure 21. Gini coefficient of the nine sample local districts dominated by (semi-)detached houses (left), linear housing estates (center) and perimeter blocks (right); dashed lines illustrate the Gini coefficient for each type of residential area (adapted from Wang et al., 2019b)

Evidently, those local districts dominated by (semi-)detached houses have a higher spatial equity of GI distribution. Moreover, their residents have much easier access to GI for further recreation. This result is emphasized in so far as this type is dominated by the residential middle class. The result primarily presents a picture of the variations in the spatial equity of GI distribution in terms of different types of residential area, but simultaneously reveals a substantial impact on the potential recreation functions of GI.

Table 6 GI-adapted Gini coefficient values for each typical local district

Typical residential local districts	GI-adapted Gini coefficient	Average values of Gini coefficient	GI equity status
i) (semi-) detached houses		0.175	Even
Meusdorf	0.14		
Grünau-Siedlung	0.10		
Marienbrunn	0.29		
ii) Linear housing since1960s		0.308	Intermediate
Grünau-Nord	0.24		
Paunsdorf	0.45		
Grünau-Mitte	0.23		
iii) Perimeter blocks (mostly Wilhelminian-style in central area)		0.402	Uneven
Neustadt-Neuschönefeld	0.36		
Südvorstadt	0.87		
Gohlis-Mitte	0.46		

4.6.5 Relationships between spatial patterns and the Gini coefficient in the residential types

According to Table 6, the order of the Gini coefficient is: (semi-)detached houses < linear houses< perimeter blocks. A detailed understanding of the prevalent types of residential area can be obtained by comparing the morphological spatial patterns and the Gini coefficient of each typical residential district separately. For comparison, the results for each type of residential area (comprising three sample local districts each) are illustrated in Figure 22, revealing the impact of spatial patterns of GI on its spatial equity.

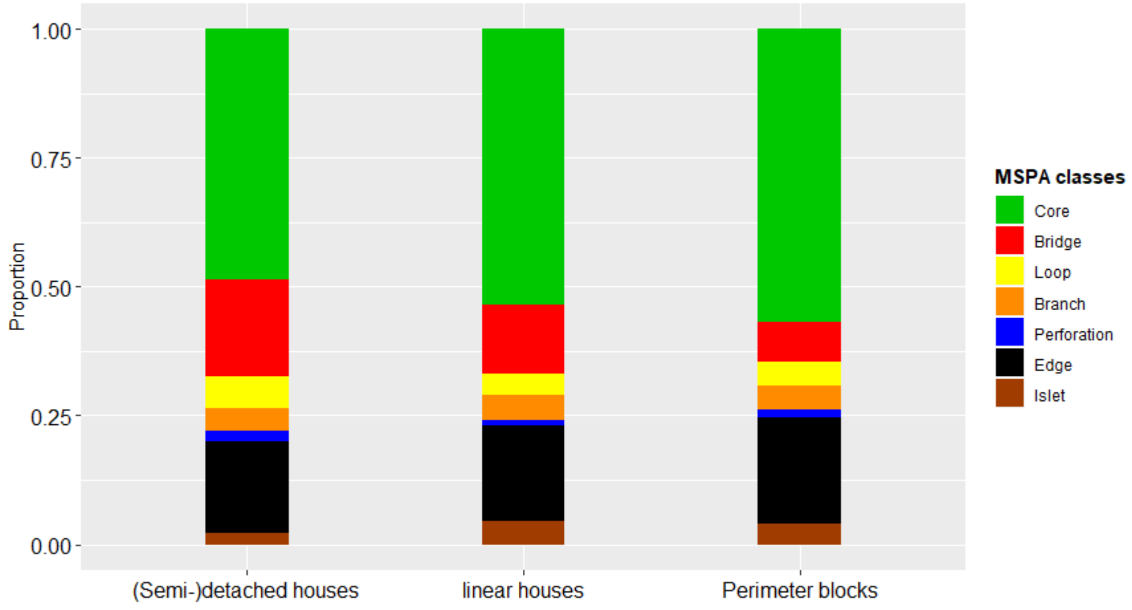


Figure 22. MSPA classes for three types of typical residential area dominated by (semi-)detached, linear housing and perimeter blocks respectively; colors correspond to color scheme used in the MSPA approach introduced by Vogt et al., (2017), adapted from Wang et al., (2019b).

The results in Figure 22 show that the spatial patterns of each type are different, even though the GI core accounts for the biggest fractions among all three different structural areas. One significant result demonstrates positive correlations between GI bridge and edge patterns with the spatial equity of GI distributions. That is to say, for the type of residential area dominated by (semi-)detached houses, there are a large number of GI bridges and edges which connect to other GI cores and sealed surfaces respectively, and GI distributions usually possess more equity in these predominant local districts.

With regard to the Gini coefficient index, it increases strikingly from the local districts dominated by (semi-)detached houses to perimeter blocks. GI distributions in districts dominated by row houses are the most unequal, while those local districts with (semi-)detached houses possess GI with a high level of spatial equity. For the same types of building structure, the distributions of spatial patterns are quite similar to the result shown in Figure 5. For instance, for those local districts dominated by (semi-)detached houses, the bridge (GI core connected to another GI core) and edge (GI core to built-up areas) in all the proportions of both bridge and edge are quite similar. This means that these GI cores are well connected, but they are also vulnerable in terms of their potential transition to built-up areas. The differences between edge and bridge areas in these local districts are inconspicuous.

What stands out in Figure 22 is that there are obvious distinctions between fractions of bridge and edge in those local districts dominated by linear housing and perimeter blocks. The proportions of bridge patterns are even less than half of the edge patterns in residential areas dominated by linear housing and perimeter blocks. As a result, the connectivity of one GI core to a different GI core is relatively limited compared to residential areas where there are mostly (semi-)detached houses. Overall, for these three different types of residential area depicted in Figure 5, the GI cores do not provide a guarantee for the spatial equity of GI, namely the low Gini coefficient.

DISCUSSION

“We must have a system of ecological concepts which will allow of the inclusion of all forms of vegetation expression and activity.
We cannot confine ourselves to the so-called "natural" entities and ignore the processes and expressions of vegetation now so abundantly provided us by the activities of man.
Such a course is not scientifically sound, because scientific analysis must penetrate beneath the forms of the "natural" entities, and it is not practically useful because ecology must be applied to conditions brought about by human activity.
The "natural" entities and the anthropogenic derivate alike must be analyzed in terms of the most appropriate concepts we can find.”

(Arthur Tansley)

5 Discussion

5.1 Challenges of using an inclusive definition of the green infrastructure term

Numerous publications have demonstrated the value of ESS in terms of linking green space development and conservation to environmental health, human health, security and well-being (Millennium Ecosystem Assessment 2005; Brauman et al. 2007; Müller et al. 2010; TEEB 2010; McPherson et al. 2015). The complexity of quantitatively assessing many specific ES has made it difficult to incorporate them into planning tools in ways that are credible and replicable (Daily et al. 2009; Hansen and Pauleit, 2014). In the specific context of urban GI, planning frameworks often focus on a single ES across different GI types (Norton et al. 2015) or on a single GI type across various ESS (Dobbs et al., 2011). The methodology (in **Paper II**) and findings (in **Paper II** and **Paper III**) explain the challenges in this respect.

Meanwhile, the processes of constructing an urban GI typology (Section 4.3) and an integrated indicator-based framework (Section 4.4) and presenting the argumentation for GI functional/structural connectivity (Section 4.6) pose major challenges to advocating urban GI planning. These difficulties mainly lie in the following aspects:

1) The supply and demand of ESS across different GI types are inconsistent.

2) Both GI and ESS can be different at various spatial scales.

3) The multiple ESS provided by GI are changeable at different spatial scales, i.e. at global, continental, national, regional and city levels.

Another challenge underlying these difficulties is that, as findings (in **Paper I**) show, there is the troublesome issue of conceptual ambiguity and the widespread citation of GI-related concepts (in Table 1). This challenge has also been recognized in the debates held as part of the Royal Town Planning Institute Yorkshire Conference Series (Wright, 2011), under the title of "*Green Space, Green Belt and Green Infrastructure*" (24 February, 2010, in Leeds). Here, it was argued that GI has tended to be an ambiguous and 'corruptible concept' that generates confusion (Collinge, 2010), since potential environmental damage might be justified by other environmental benefits (Wright, 2011). It is important to note that the ambiguity of GI can easily be co-opted by certain political agendas, thereby hindering its practical application. As potential users/advocators/scholars in the field of urban GI planning, I think we have to be aware of, and sensitive to, the risks and problems in the GI concept itself due to the inclusive definition of the GI term in the context of ESS. It is highly advisable to pay particular attention to certain kinds of cross-references that might aggregate the aforementioned risks when it comes to putting the GI concept into practice.

5.2 Urban green infrastructure as a planning concept

As mentioned in the literature review (**Paper I**), urban GI planning has, thus far, been part of urban planning only to a limited extent. This dissertation shows how two key features of urban GI in particular, multifunctionality (**Paper II**) and connectivity (**Paper III**), can be assessed for their potential use in urban planning. Furthermore, as equity forms a link between social and environmental sustainability (European Commission, 1996), this dissertation explores the aspects of equity pertaining to access to urban GI in order to underscore the high significance of equity in sustainable urban development. Both multifunctionality and connectivity may be employed in advocating urban GI as a strategic planning method/tool towards urban sustainability.

By applying the urban GI concept in the urban areas of Leipzig, Germany (**Paper II**), this thesis has provided an integrated indicator framework for multifunctional GI assessment, for the purpose of potential application in other contexts. Although the multifunctional character of GI has to some extent been addressed in **Paper II**, the conceptual and practical difficulties of assessing it, taking into account the variety of stakeholders and contexts, has not yet been captured. In addition, this dissertation has emphasized the significance of connectivity, examining it across typical residential areas (**Paper III**). Using the MSPA approach, it includes comparative analysis and focuses on spatial equity for urban residents by making full use of high resolution spatial datasets. However, a major drawback of this case study is the lack of input from urban green space users. The limitations in the data availability and indicator calculations (both in **Paper II & III**) have shown that integrating urban GI planning into urban planning is not only a challenge for nations like Germany, the UK or China, but, because of GI's multifunctionality and connectivity, also an attractive solution in terms of understanding multiple ESS (**Paper II**) and alleviating social inequalities in green spaces (**Paper III**).

Overall, both of these applications have enhanced urban GI as a planning concept focused on realizing a good quality of life for citizens. Together, they contribute to the characterization of urban GI as a planning concept focused on mitigating the growing pressures on ecosystem services in cities.

5.3 Approaches to supporting urban green infrastructure planning

From a spatial point of view, methods of characterizing urban GI planning should enable spatial analysis of GI configuration. It may be beneficial to employ spatial patterns analysis. In order to describe the spatial patterns, various methods and tools have been developed and applied in urban ecology (e.g. McGarigal and Marks (1995), Kim and Pauleit (2007), Kuttner et al. (2013)) that reveal the links between urban GI patterns and ecological and social functions (Luck and Wu, 2002).

The mainstreaming approaches comprise Fragstats (Luck and Wu, 2002; McGarigal et al., 2002; McGarigal and Marks, 1995) – which provides a series of landscape metrics (e.g. area/density, patch shape index and proximity metrics) for detecting the urbanization gradient of landscape patterns (Kupfer, 2012; Luck and Wu, 2002) and biodiversity conservation (Kim and Pauleit, 2007) – and tools such as least cost measures (Sutcliffe et al., 2003) and genetic patterns, which offer a more ecologically oriented approach to quantifying spatial patterns (e.g. Chardon et al. (2003); Coulon et al. (2004); Hokit et al. (2010). Other graph-based approaches are also applied, for instance, the Conefor Sensinode tool (Saura and Torne, 2009), which quantifies habitat patches for connectivity by calculating nodes, links and graph-based metrics, including the number of links, the number of components, the integral index of connectivity, and so forth; or the Circuitscape tool (McRae and Shah, 2009), which can calculate and map measures of resistance, conductance, current flows and voltage. These are widely utilized in analyzing structural landscape metrics and connectivity, but they are all rooted in graph, network, and circuit theory (Kupfer, 2012) and are limited by inconsistent evaluation results from human interpretation (Kupfer, 2012; Ostapowicz et al., 2008). Their definitions of thresholds such as patch width are in terms of selected contexts. With regard to methods that analyze spatial patterns, the former, i.e. structural indices of patch shape such as perimeter to area ratio, and the latter, i.e. graph-based approaches, can explore the importance of corridors as connectors between nodes (Ostapowicz et al., 2008) in a network, but only after these corridors have been defined elsewhere.

One step forward in this respect is the morphological spatial pattern analysis (MSPA) approach, developed by Vogt et al. (2006) and Soille and Vogt (2009), which has evolved separately from the aforementioned methods: it can map corridors as structural links between core patches, but this feature cannot be achieved with any other methodologies (Kupfer, 2012), neither landscape metrics (structural indices) nor graph-based approaches. Indeed, MSPA is a mathematical morphological algorithm that performs a segmentation analysis of foreground objects against a background matrix (ibid.), and is also a tool for describing spatial patterns and connectivity in urban GI (Ramos-Gonzalez, 2014). MSPA makes pattern analyses more interpretable by incorporating visualization maps and classifying and mapping individual pixels into different categories, such as core, bridge, loop, branch, perforation and edge (Barbati et al., 2013). MSPA (Vogt et al. 2009) therefore offers an effective approach to investigating GI in heterogeneous urban areas, allowing us to identify and quantify spatial patterns of GI (Nielsen et al., 2016) and distinguish between them, e.g. bridges as connectivity for species dispersal and movement (Barbati et al., 2013). To date, the MSPA approach has been used primarily in forest areas (Barbati et al., 2013; Goetz et al., 2009; Riitters, 2011) to detect forest connectors (Saura et al., 2011), to monitor forest composition and configuration (Ostapowicz et al., 2008), in ecological restoration areas for site prioritization (Wickham et al., 2017), and in riparian zones to identify the structural riparian corridors for conservation and management purposes (Clerici and Vogt, 2013). For the purposes of this thesis, I tested the capacity of MSPA to address spatial equity in urban residential areas, and I found it to be very effective.

5.4 Applying the concept of urban ecosystem services to the planning of urban green infrastructure at city scale

For the GI assessment and planning, we provide a number of indicators for capturing multiple GI functions in urban areas, such as carbon storage from green areas, allotments and community gardens for food self-supply, river-adjacent GI for water regulation, and recreation spaces. Instead of merely identifying isolated grid cells with high values of GI functions, this approach helps to identify the hot/cold spots for these different GI functions, as well as the spatially aggregated multifunctional areas (Brown, 2008; Peng et al., 2019).

It is widely suggested that the values of GI functions in hot spot areas are significantly higher than average (De Vreese et al., 2016). This information may facilitate GI planning because it helps to identify sites/areas with higher multifunctionality, whereas at locations recognized as cold spots, potential GI plans aimed at creating access to recreational spaces (e.g. for walking or jogging) in order to promote human health and well-being, or aimed at planting street trees for urban heat island mitigation, may be appropriate in increasing the multifunctionality of GI. In my case of Leipzig, it can be clearly seen that a large percentage of multifunctional GI traverses municipal districts (Figure 16). In terms of GI assessment and planning in the City of Leipzig, this means there is a demand for planning collaborations beyond local districts, especially for those local districts to the west of the city center such as Grünau, Schönau, Neulidennau, and Leutzsch, to realize multifunctionality in GI. Green space planning and management therefore have to transcend administrative boundaries and the spatial relations of multiple GI functions in order to establish multifunctional GI networks.

In summary, the application of the AMGI framework enabled us to identify and assess 26 types of GI elements in total. Compared with the proposed GI typology in Section 4.3 (listed according to the intensity of human influence/association with GI in Table A5), the results in Section 4.5 cover 57% of GI types in the whole typology. Previously, GI analysis was either limited to some types with few connections to GI functions or only associated with one or two functions (European Commission, 2012; Madureira and Andresen, 2014; Wang and Banzhaf, 2018).

Despite this, a limitation of the exemplification is that due to the conceptual and methodological focus of the study, I was not able to explore in greater depth the synergies and trade-offs of GI in relation to various local policies and strategies. Furthermore, the weighting of the various GI functions for a contextualized assessment of multifunctionality was not feasible, due to the lack of information on the preferences of different stakeholders (Hansen and Pauleit, 2014; Pauleit et al., 2019a). Therefore, in the application to Leipzig, I mainly focused on the supply of ESS provided by GI, instead of on the demand for ESS. In addition, I primarily included indicators covering the ecological and socio-cultural dimensions, yet very few from the socio-economic and human health dimensions. The latter was mainly due to limited data availability. Nonetheless, it is precisely these restrictions reflected in my exemplification that show the substantial demand for interdisciplinary and transdisciplinary research and collaborations, particularly among RS experts and GIS scientists on the one and experts in governance and urban planners on the other side.

When testing the applicability of my assessment framework to a European city, it is clear that there is a necessity for AMGI using remote sensing-based methods and products. This thesis therefore draws attention to the need to strengthen the urban GI assessment using RS-based and GIS-based techniques. From this point of view, the proposed integrated framework and its application in this thesis will help foster the creation of a common language for better mutual understanding among scientists and stakeholders, given that a clear framework is crucial for the sustainable management of spatially-oriented GI plans over time and among various stakeholder groups. This is quite challenging in GI assessment and planning, but it is essential in furthering the investigation, enhancing the synergies and reducing the trade-offs (Hansen and Pauleit, 2014) of multiple GI functions.

5.5 The assessment of multifunctional green infrastructure as a guiding framework

The indicator-based framework proposed in the thesis permits the use of an ESS framework to evaluate different types of GI and their functions and benefits. Translating the aggregated effects of ESS into a holistic strategy for urban GI planning is a significant step forward in terms of the value of the concept of GI. However, there are still major challenges as regards the transferability and translation of the entire framework into different location-specific GI planning.

5.5.1 Evaluation of the integrated indicator framework

What stands out when comparing and analyzing indicator frameworks I to III is the potential contribution these frameworks make to the conceptual development of GI. This has enabled us to develop an integrated framework and methodology for AMGI, accounting for the urban sustainability dimensions of ecology, socio-economy, socio-culture and human health. My indicator-based framework therefore advances a more complex analysis of GI through the incorporation of a multidimensional analysis focused on sustainability, as well as through the provision of ten GI benefits that potentially facilitate the capture of multiple GI functions. The strength of my proposed framework is that it provides an easy-to-handle pool of indicators (Table A.1 to A.3) for a comprehensive urban GI typology (e.g. Table A.5) for potential applications in AMGI. The integrated indicator framework and assessment methodology both form an informative toolbox for undertaking an integrative GI assessment.

It is widely agreed that AMGI is an intricate process, not only because of the diversity and uncertainty of the GI concept itself (Benedict and McMahon, 2006; European Commission, 2012; European Environment Agency (EEA), 2011), but also since the multiple functions of GI are difficult to capture in full (European Commission, 2012; European Environment Agency (EEA), 2011). Compared with the conceptual framework for multifunctionality in GI planning for urban areas by Hansen and Pauleit (Hansen and Pauleit, 2014), this study supplies an indicator-based framework and a holistic GI assessment methodology, while assuming the multifunctionality of GI as a given principle. Both the framework for multifunctionality in GI planning by Hansen and Pauleit (Hansen and Pauleit, 2014) and the framework we are proposing here reinforce the significance of GI planning from an ecological and social perspective. In terms of bringing something new to the debate, the latter addresses these two perspectives by taking indicators as proxies and classifying each indicator in terms of ecological, socio-economic, socio-cultural and human health dimensions. Notwithstanding, my indicator-based framework covers multiple GI functions and incorporates the latest conceptual evolution of GI as first priorities. Nevertheless, it pays little attention to the synergies and trade-offs between different GI functions and stakeholder preferences (Hansen and Pauleit, 2014). These have promising implications for a multifunctionality assessment of GI (ibid.), and they ought to be further analyzed based on this integrated indicator framework.

Although it has been stated that ESS provided by GI, the multiple benefits and functions of GI, and a potential shift towards a green economy are three major aspects (Wang and Banzhaf, 2018; Wang et al., 2019a) in GI assessment, only the former two are addressed in the exemplification of **Paper II**. Despite this, the framework provided demonstrates the possibility of addressing the green economy dimension via indicators such as employment within directly GI-related sectors (agriculture, forestry and fisheries) and the increment economic values of residential land and property at a distance of 1 km from green spaces (Morancho, 2003), thereby emphasizing the significance of a shift towards a green economy (Pauleit et al., 2019a).

With respect to the question of whether the enclosed indicators are applicable, measurable, or even transferable, further analyses and potential compromises on the indicator selections must be carried out in different cultural and geographical contexts. For instance, to assess urban biodiversity, indicators such as the capacity of ecosystems to sustain the activity of insect pollinators has thus far only been available through ecosystem services mapping at European scale (ESTIMAP) (Maes et al., 2017; Zulian et al., 2013). The respective method for ecological modeling for an urban evaluation, i.e. the urban version of the ESTIMAP-P (Maes et al., 2019) model for pollination, is still under development, since an adaption of LULC and the distance to semi-natural vegetation patches (ibid.) call for a high quality of RS information to capture the spatial heterogeneity in urban settings.

5.5.2 The transferable potential of integrated indicator framework and methodology

Exemplifying the assessment approach may help to better understand the indicator framework and methodology in Section 4 that foster or hinder the AMGI in different contexts. For the purpose of a clear illustration and full exploration of my framework when applied to Leipzig, I selected at least one indicator for each GI benefit. Whilst running the whole methodology (from stage 1 to 3) in one European city, it can be clearly seen that the application of an integrated framework (in **Paper II**) calls for a comprehensive review of local studies (e.g. (Kubal et al., 2009; Schwarz et al., 2012; Strohbach and Haase, 2012) as well as an extensive understanding of spatial datasets for the AMGI. For example, the selection of earth observation datasets, i.e. Urban Atlas data, biotope mapping and local LULC data, was based on an underlying analysis focused on their contributions to AMGI and taking into account the spatial resolution of each and their respective classification of urban spatial categories (at least into their secondary classes).

The entire methodology in this thesis (Section 3.4) can be applied to other European cities and may also inspire other cities where similar remote sensing information is available. Likewise, the publicly available RS datasets, e.g. the CORINE and Urban Atlas datasets delivered by the European Environment Agency (EEA) and the European Commission DG Joint Research Centre (JRC) (https://land.copernicus.eu/), have greatly increased the transferability of the methodology of GI assessment, as these datasets cover 39 countries in Europe. Moreover, biotope mapping has been shown to make a substantial contribution to AMGI at urban scale, given that it has contributed to the evaluation of GI benefits for natural resources, tourism, recreation and conservation. Therefore, there is more potential for the method to be used for the areas where there is biotope mapping on the basis of investigations of individual habitats (in Section 3.4.2).

For the cities where there are spatial datasets at high spatial resolution, the indicator framework (in Section 4.4), the assessment methodology (in Section 3.4.2) and the MSPA approach (in Section 3.4.3) may be widely transferable, since they are all ready to be applied to other cities and have proved effective in identifying both the hot spots of respective GI functions and the multifunctional areas. Moreover, the indicator Getis Ord Gi* we selected in the methodology for the identification of hot/cold spots of GI functions is not limited to the urban scale. It can be used at various scales, such as regional, metropolitan, and local scales. Accordingly, the earth observation data and the simple and efficient method for hot spot analysis both contribute to the potential application of my framework and methodology.

5.6 Limitations of the thesis

In this thesis, in order to underscore the role of urban GI, I highlight the principles of multifunctionality and connectivity in urban GI as potential solutions. The limitations of the thesis also apply to these principles.

5.6.1 Limitations of the framework for assessment of multifunctional green infrastructure

In order to inspire and provoke more studies for improving AMGI in practice, I propose two dimensions in the multifunctionality of GI (in **Paper I**). The first dimension consists in multiple functions within one specific area. The second dimension refers to the functions of GI at multiple scales and the various interconnected roles of GI as networks that enhance structural and functional connectivity. This thesis only covers the first dimension; it considers as many GI functions as possible without exploring the synergies between multiple GI functions (in **Paper II**). One weakness of this study is therefore the lack of exploration of structural and functional connectivity. Nonetheless, the thesis provides an essential basis for it by presenting an integrative indicator framework for AMGI as well as exemplifying its usage in Leipzig. As for potential synergies and trade-offs, a comparative analysis should be undertaken that includes different spatial changes across a particular time span.

The findings of this thesis are limited by the lack of long-term synergies and trade-offs. The spatial and temporal changes of multifunctional GI would be a significant direction for research in the near future.

Another limitation pertains to the findings on the connectivity of GI in the samples study (in Section 3.4. and Section 4.6). To explore the role of urban GI as significant and strategic networks in urban areas, a variety of spatial patterns of urban GI were compared and analyzed (in **Paper III**), based on my own defined patterns and the differentiated intensity of their connectivity. However, because this thesis is restricted to morphological perspectives and limited by the methodology, difficulties arise in the attempt to discuss functional connectivity in depth. Thus, this thesis overlooks the functional connectivity of urban green spaces in reality due to a lack of real information from inhabitants and local users of, or communities within, green spaces, and even a lack of expert evaluations.

These limitations in terms of application (in **Paper II** and **Paper III**) clearly suggest that GI planning requires high-quality earth observation datasets, such as the upcoming Copernicus data, the RS data on the biosphere (e.g. on the fraction of photosynthetically active radiation absorbed by the vegetation) and on oceanography (lake surface water temperature) at the spatial scales from 1km, 300m or even lower, as well as the information from local users and species/habitats. These may provide more insight into GI strategies by revealing substantial GI functions that are not yet available in case studies, albeit they are already proposed in my integrated framework. To support multifunctional GI analysis, therefore, it is necessary to combine remote sensing-based and GIS-based techniques at various spatial, temporal, and spectral scales. For instance, incorporating indicators such as leaf area index (LAI) at global scale (i.e. employing a remote-sensing-based method using an improved MODIS LAI product at 1 km spatial resolution (Zhu et al., 2013)). Likewise, according to my framework, it is also necessary to evaluate leaf area density (LAD) at local scale, i.e. employing high-resolution terrestrial light detection and ranging (LiDAR) (Li et al., 2017), to retrieve the three dimensional (3D) structure properties of vegetation. Here, remote-sensing-based methods would contribute considerably to obtaining respective indicators and to the evaluation of GI functions in reduced water runoff and cooling effects. Integrating the 3D information in order to enrich indicators for GI assessment and planning is likely to be one of the key topics in further multifunctional GI research.

5.6.2 Limitations of the multifunctionality analysis for urban green infrastructure planning

I have observed a trend towards addressing multifunctionality in GI in a large number of publications over the past few decades. As the Landscape Institute (2009) claims:

> *Functions are multiplied and enhanced significantly when the natural environment is planned and managed as an integrated whole; a managed network of green spaces, habitats and places providing benefits which exceed the sum of the individual parts. It is this concept of connectivity and multifunctionality which makes the GI approach such an important part of landscape planning and management.*

From a spatial point of view, this thesis concludes that three types of multifunctionality may be employed at different spatial scales. These are:

1) The spatial combination of different green space networks within various functions.
2) Combinations of differentiated functions as functional networks at the same time.
3) Different kinds of GI functions of natural and semi-natural networks over separate temporal scales.

The first two were explored in **Paper II** and **Paper III** separately, but the third type is not included in this thesis. This type may include the synergies and trade-offs of various GI functions, either at different spatial scales or across different time spans. The synergies and trade-offs of multiple GI functions at different scales in the long term might be a promising direction in innovative urban planning for the purpose of improved urban resilience. However, it requires a large number of well-organized, high-quality and long-term data pertaining to the observation of ecosystems and spatial analyses, which may greatly contribute to the enhancement of multifunctionality.

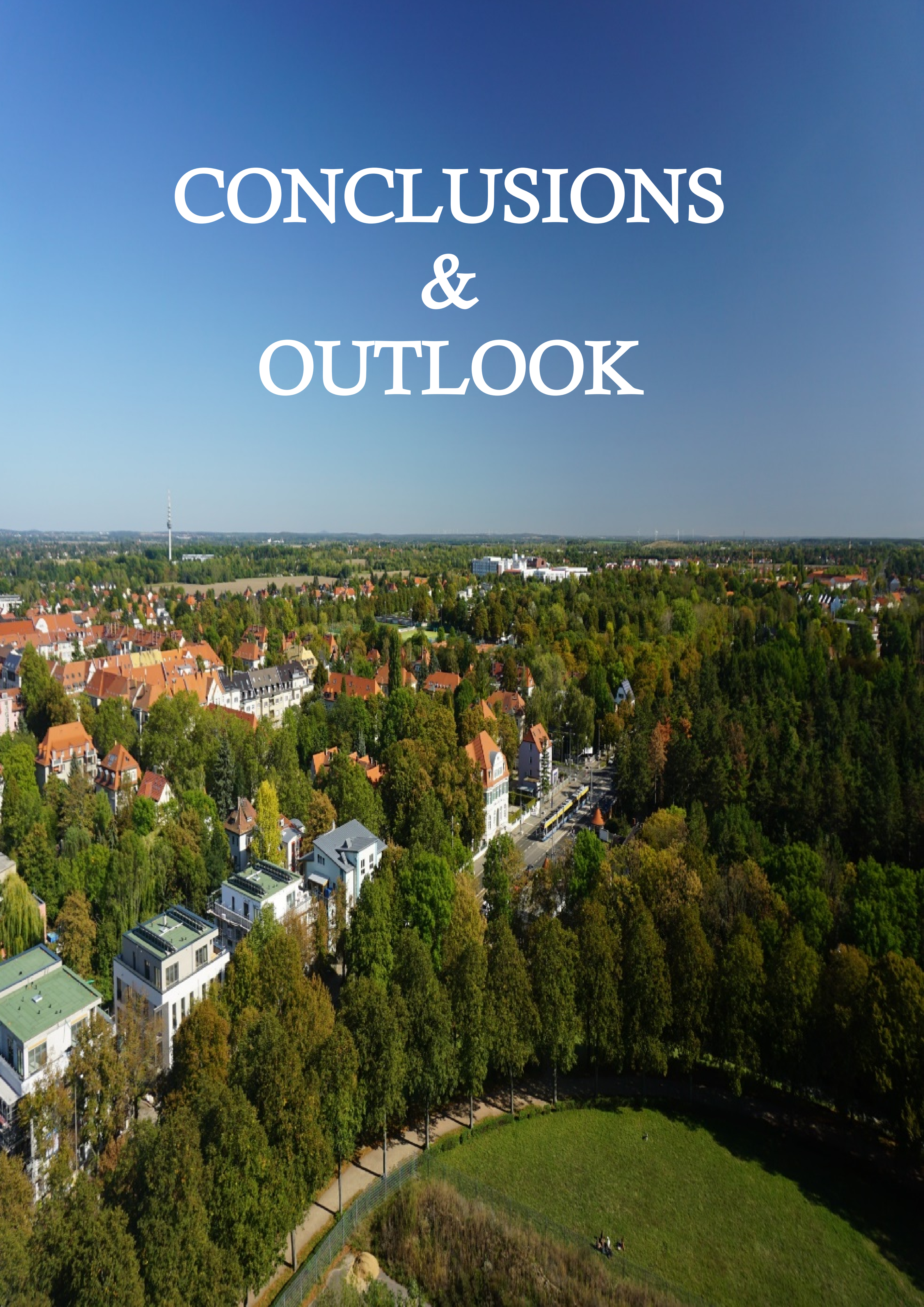
5.6.3 Limitations of the connectivity analysis for urban green infrastructure planning

Urban GI in its essence consists in interconnected networks of humans and aspects of nature. Urban GI necessitates planning that takes connectivity into consideration. The potential negative impact of fragmentation places the burden on urban planning to conserve significant ecological corridors and biodiversity hot spots, as well as enhance habitat management, networks and connectivity in order to bring about ecological and wider social benefits.

In this thesis, with ecological connectivity as its primary objective, I explore and present how the GI connectivity principle might be enhanced (**Paper III**). Based on a comprehensive understanding of the GI concept as well as the advantages and disadvantages of GI mapping (**Paper I**), I use the MSPA approach to explore the spatial arrangement of built features in urban areas and of ecological corridors (GI core, branch and corridor), taking urban morphology into consideration.

However, the core of the connectivity principle of urban GI comprehends both **structural** and **functional** connectivity. Structural connectivity is the extent to which habitat patches in landscape are physically linked (**Paper III**). Studying structural connectivity using morphological methods (e.g. the MSPA approach) means looking at urban green spaces from human perspectives (Harrison et al., 2016), but it might overlook the interactions and dynamics of urban residents and animals in terms of how they move through and explore urban green spaces, and in terms of the impact of their activities on ecosystems. Functional connectivity is usually sensitive to different species and contexts, so it is quite difficult to measure the supply and demand in terms of the functional connectivity of species and people.

CONCLUSIONS & OUTLOOK



“The point of cities is the multiplicity of the choice.”

(Jane Jacobs)

6 Conclusions

6.1 Main findings

It is well known that urban ecology is a relatively recent scientific discipline with a human ecology orientation that is of great use with respect to worldwide problems (Breuste et al., 2013). The findings of this thesis may contribute to urban ecology in the context of the urban GI concept.

For the purpose of providing methods for urban GI planning, I have summarized the primary findings of this thesis in Table 8, which is primarily focused on three aspects. As listed in Table 8, they correspond to the three stages of the doctoral project overall: 1) Defining the urban GI concept, including its multifunctionality, 2) Developing assessment methods for multifunctional GI, and 3) Understanding GI as a structural (strategic) planning tool for steering cities in an ecological direction.

The findings listed here incorporate the following aspects: the urban GI concept of multifunctionality, the assessment of multifunctional GI, and GI as a structural (strategic) planning tool for steering cities in an ecological direction. The findings include recommendations on urban GI planning for the case study areas and striking findings from Paper II and Paper III.

Table 7: Overview of key findings of dissertation

Urban GI concept: multifunctionality

- Multifunctionality of GI is the feature best suited to enhancing the GI concept.
- There has been an increase in GI mapping at the urban scale since 2014.
- The MSPA approach is especially suitable for GI planning, as it distinguishes structure from the spatial relationships existing among different urban structures.
- There is a bottleneck of narrow focus on single functions when considering GI-related categories.
- In the past decade GI has been applied in land-use and conservation plans, mainly in urban areas.
- GI functional analysis is still lacking in most of the literature, and the representative research has focused mainly on GI functions (regulation of water flows, temperature control, and accessibility to recreation services).
- Identification of the most prominent aspects of GI in order to steer it in a more efficient direction: 1) improving ecosystem functioning and promoting ESS, 2) promoting societal well-being and health, 3) protecting the state of ecosystems and biodiversity, and 4) supporting the development of a green economy and sustainable land and water management.
- The Chinese approach of designing/planning security patterns for GI implementation contributes to GI mapping methods.
- The multifunctional GI assessment, ideally, should include the qualities of GI elements and the qualities of the conservation and management of urban ecosystems.

Assessment of multifunctional GI

I. Practical findings/recommendations specific to the sustainable urban development of Leipzig:

- For urban areas in Leipzig, there is a clear spatial concentration of recreation function in the central western part of Leipzig, and the urban forest alluvial plays a significant role in multifunctionality for residents.
- For the City of Leipzig, there are no connections between hot spot areas and multifunctional areas. There is a large percentage of multifunctional GI across municipal districts.
- There is an apparent demand for collaborations beyond local districts, especially for those local districts in the west of Leipzig, such as Grünau, Schönau, Neulindenau, and Leutzsch, to realize the multifunctionality of GI.
- Green space planning and management in urban areas ought to transcend administrative boundaries and the spatial relations of multiple GI functions in order to establish multifunctional networks in GI.

II. Key findings for AMGI methods and GI assessment in general:

- A multidimensional analysis requires an indicator framework that takes into account all aspects (i.e. ecological, socio-cultural, socio-economic and human health) of urban sustainability.
- When conducting an AMGI at various spatial and temporal scales, three significant aspects should be considered: ESS provided by GI, the multiple benefits and functions of GI, and a potential shift towards a

green economy.

- Using the Getis Ord index may help in identifying the spatial distribution of the hot/cold spots of GI functions and then in mapping GI multifunctionality.
- The proposed indicator-based framework for the multifunctional GI assessment is valid at urban scale and may be transferable to other European cities where public remote sensing datasets such as CORINE and Urban Atlas are available.
- Biotope mapping substantially contributes to the evaluation of GI benefits in natural resources, tourism, recreation and conservation, due to its valuable categories of biotopes and its specific investigation of individual habitats.

GI as a structural (strategic) planning tool for steering cities in an ecological direction

I. Practical findings/recommendations specific to the sustainable urban development of Leipzig:

- For a city like Leipzig, which is undergoing re-growth, enlarging the existing green core areas would merely lead to a limited increase in the spatial equity of GI distribution, and therefore seems less favorable.
- In Leipzig, the options for GI bridges may provide structural connectivity from one core green area to different core areas and simultaneously contribute substantially to GI equity.
- Especially in Leipzig residential areas, urban GI planning should, in particular, strive to enhance connectivity in order to attain urban sustainability.

II. Key findings for GI planning as strategic networks:

- Morphological spatial pattern analysis serves strategic urban GI planning. The customized definitions of various spatial patterns can also be used in other GI plans to analyze the GI principle of connectivity.
- GI bridges contribute not only to the ecological structural connectivity but also to the spatial equity of GI.
- GI bridges are significant for equity; it is therefore advisable that they be restored or built in order to provide more equal green spaces.
- It is noticeable that GI core areas do not firmly ascertain a high level of spatial equity.

6.2 Transferability of results and recommendations for the integration of urban green infrastructure into urban planning

This dissertation is intended as a contribution to GI development and planning in urban environments, adding to the growing debate regarding cities and sustainability all over the world.

Overall, it considers a wide range of ideas pertaining to significant issues around strategic GI management for sustainable urban development. Despite a growing raft of discussions, directives and plans for green cities, both European and Chinese cities are exposed to environmental, economic and social problems and the negative effects of climate change. Creative approaches to green space planning and the management of urban ecosystems should be explored and further improved so that cities can both solve local problems and contribute to regional and global sustainability.

This thesis draws specific attention to the urban GI concept and its principles of multifunctionality and connectivity by applying this concept to two case studies (**Paper I** & **II**), although six principles (sustainability, multifunctionality, connectivity, biodiversity targets, urban focus and inter- and transdisciplinary collaboration) of urban GI planning are discussed and proposed as part of a far-reaching conceptual evolution of GI (in **Paper I**). Overall, the thesis addresses the thematic aspects below.

6.2.1 Contributing to the multi-dimensions of sustainability via urban green infrastructure

The thesis provides an indicator-based framework for AMGI, including GI functions represented by a series of indicators. Each indicator included in this framework has been classified into different dimensions for urban sustainability. These are based on the studies of each indicator from their sources in **Paper II**. The integrated indicator framework for AMGI in this thesis provides a series of indicators – multi-dimensions explicitly focused on urban sustainability – for multiple GI functions. It recognizes the diversity of European and Chinese cities, therefore suggesting neither blanket solutions nor prescriptions or panaceas for all cities. It makes this point clearly when applying the entire indicator framework for AMGI to the City of Leipzig, Germany. Instead, it advocates the provision of supportive frameworks within which cities may explore innovative methods appropriate to their local contexts, taking into account the range of local management and planning expertise and circumstances. Urban planners, landscape architects, city managers/administrators and scientists may refer to the multidimensional indicator-based framework to optimize their GI plans and implementation.

6.2.2 Analyzing ecological connectivity for urban green infrastructure planning

The multiple benefits of renaturing cities are better observed if green and blue spaces are connected in a cohesive network. For a growing city like Leipzig, the options are either to enlarge existing GI core areas or to enhance GI bridges, and meanwhile to reinforce spatial equity of GI for sustainable urban development. My study provides evidence that enlarging the existing GI core areas would only lead to a limited increase in the spatial equity of GI distribution, and therefore seems less favorable. The option for GI bridges provides structural connectivity from one GI core to different GI cores. It will therefore contribute substantially to GI equity. This suggestion is based on my combined methodology of MSPA and GI equity measurement (GI-adapted Gini coefficient index). In light of this, urban GI planning should specifically strive to enhance connectivity. GI planning in essence is a strategic planned network for improving structural and functional connectivity. The MSPA method and the analysis of the GI-adapted Gini coefficient can reveal GI spatial patterns and distributions, thus providing more information to contribute to the overall goal of sustainability.

In terms of GI planning addressing connectivity, one significant conclusion is that it is extremely important and beneficial to plan the network of corridors and remnant patches of urban green and blue spaces well in advance of urban development in order to yield better connectivity, optimum corridor lengths, less habitat fragmentation, better links to regional preserves, and better control of patch size and shape.

6.2.3 The integrated indicator framework for assessment of multifunctional green infrastructure

This thesis delivers an initial approach to conducting AMGI within a spatially explicit methodology. By providing an integrated indicator framework, I intend to draw attention to ESS provided by GI, the multiple benefits and functions of GI, and a potential shift towards a green economy, while conducting an AMGI at various spatial, temporal and spectral scales. I therefore recommend an assessment using my framework and methodology in three stages: i) developing a conceptual framework for priority setting to evaluate the requirements for addressing several dimensions of sustainability and multifunctionality; ii) a contextual assessment taking into account focal scale and data availability; and iii) a retrospective assessment: tracing back over the whole process when the respective AMGI is completed. As an illustrative case, I developed an AMGI in Leipzig, Germany. In this case study (Paper II), I presented the application of my proposed framework, providing at least one example for each GI benefit. With my methodology, which involved using remotely sensed information, proved quite effective, and I recommend that scholars employ my approach. My toolbox is an appealing basis for multifunctional GI assessment. It may serve as a basis for the application of AMGI in other cultural contexts. The aim of my study is to promote multi-scale research that contributes to the assessment of multiple GI functions. It is also to sow the seed for promoting multiple remote-sensing-based techniques in the acquisition of spatial indicators for GI functions and, in so doing, to advance urban GI further.

6.3 Further questions and research frontiers

A major shift that is beginning to take place, but still needs further action, is to effectively embed green infrastructure into spatial planning and view it as part of the wider infrastructure of urban areas. The thesis has raised further questions, which are listed in Box 1:

As potential answers to the aforementioned further questions, there are a number of research frontiers in the multifunctional GI concept. They cover the following aspects, as shown in Table 7:

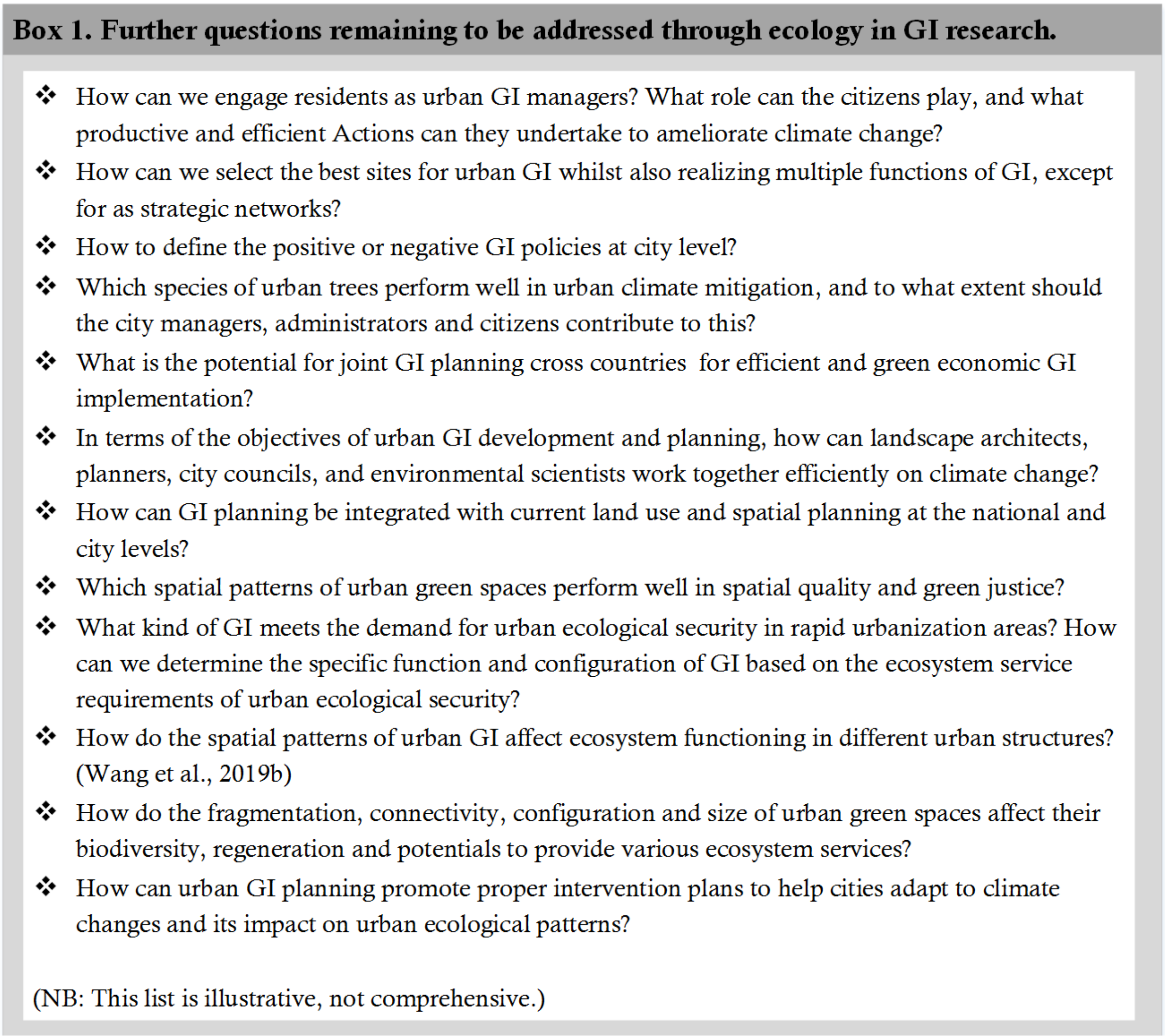
- Urban GI planning towards multifunctionality
- Ecosystem services and GI integration for urban sustainable development
- Nature-based solutions as support for GI planning
- Addressing landscape and ecological connectivity/networks via the urban GI concept
- Spatial planning for multifunctional GI to enhance resilience in cities
- Increasing investment in the natural environment

Table 8. Research frontiers and their respective remarkable works

Research frontiers	Significant papers and representative works
❖ Urban GI planning towards multifunctionality	Hansen (2018); Hansen et al. (2016); Pauleit et al. (2019b); Pauleit et al. (2019c); Grant (2010)
❖ Ecosystem services and GI integration for urban sustainable development	Burkhard et al. (2018); Maes et al. (2013a, 2016b); Maes et al. (2013b); Maes et al. (2014); Maes et al. (2019); Maes et al. (2017); Rocha (2015)
❖ Nature-based solutions as support for GI planning	(Albert et al., 2019; de Oliveira and Mell, 2019; Dushkova and Haase, 2020; Raymond et al., 2017)
❖ Addressing landscape and ecological connectivity/networks via the urban GI concept (corridors)	(Herzog, 2016; Honeck et al., 2020; Neal, 2012; Wang et al., 2019b; Zhang et al., 2019)
❖ Spatial planning for multifunctional GI to enhance resilience in cities	(Meerow and Newell, 2017; Tran et al., 2020)
❖ Increasing investment in the natural environment and GI	Greater Manchester natural capital investment plan (Greater Manchester natural capital investment plan, 2019; Mell et al., 2019), Connecting Smart and Sustainable Growth through Smart Specialization (EC, 2012)

The frontiers marked in Table 7 are important for future research and thus are expected to attract widespread attention, either as a position statement for GI concept development among city managers/administrators, landscape planners, urban planners, scientists and stakeholders in order to provoke more conversations, or as a showcase for applying the urban GI concept widely in different contexts. Future studies on the aforementioned frontier topics are therefore recommended.

In future investigations, a series of further questions, as listed in Figure 23, ought to be considered. It is important to bear in mind the possible responses to these further questions.



Box 1. Further questions remaining to be addressed through ecology in GI research.

- How can we engage residents as urban GI managers? What role can the citizens play, and what productive and efficient Actions can they undertake to ameliorate climate change?
- How can we select the best sites for urban GI whilst also realizing multiple functions of GI, except for as strategic networks?
- How to define the positive or negative GI policies at city level?
- Which species of urban trees perform well in urban climate mitigation, and to what extent should the city managers, administrators and citizens contribute to this?
- What is the potential for joint GI planning cross countries for efficient and green economic GI implementation?
- In terms of the objectives of urban GI development and planning, how can landscape architects, planners, city councils, and environmental scientists work together efficiently on climate change?
- How can GI planning be integrated with current land use and spatial planning at the national and city levels?
- Which spatial patterns of urban green spaces perform well in spatial quality and green justice?
- What kind of GI meets the demand for urban ecological security in rapid urbanization areas? How can we determine the specific function and configuration of GI based on the ecosystem service requirements of urban ecological security?
- How do the spatial patterns of urban GI affect ecosystem functioning in different urban structures? (Wang et al., 2019b)
- How do the fragmentation, connectivity, configuration and size of urban green spaces affect their biodiversity, regeneration and potentials to provide various ecosystem services?
- How can urban GI planning promote proper intervention plans to help cities adapt to climate changes and its impact on urban ecological patterns?

(NB: This list is illustrative, not comprehensive.)

Figure 23 Further questions to be addressed through urban ecology in GI research

In conclusion, this thesis, from the point of view of planning, defines urban GI as a planning concept aimed at providing strategic plans for multifunctional and well-connected green and blue spaces for residents within urban areas. Considered as an ecologically-based approach, urban GI is reinforced in this thesis as a planning concept that moves beyond traditional land-use and urban planning in order to enhance urban resilience and sustainability.

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APPENDIX

“In dwelling, live close to the ground.
In thinking, keep to the simple.
In conflict, be fair and generous.
In governing, don't try to control.
In work, do what you enjoy.
In family life, be completely present.”

(Lao Tzu)

Appendix: Tables

List of appendices:

Table A. 1 Indicator framework I for ecosystem services (ESS) assessment, from MAES, classified in terms of four dimensions, i.e. ecological (green), socio-economic (yellow), socio-cultural (purple) and human health (red). (Regarding the references for each indicator listed in the indicator framework, I refer to the fourth report from MAES [22] (pp. 71-81)), adapted from Wang et al., 2019a.

Code No. (00) for Indicator Framework I	Indicators Adapted from CICES & MAES	Ecology	Socio-Economy (SE)	Socio-Culture (SC)	Human Health (HH)
	Provisioning				
01	Production of food (ton ha^{-1} $year^{-1}$)	🟩			
02	Surface of community gardens / small plots for self-supply (ha)		🟨	🟪	
03	Drinking water provision (m^3 ha^{-1} $year^{-1}$)	🟩			
04	Drinking water consumption (m3 $year^{-1}$)		🟨		
05	Water provision (m^3 ha^{-1} $year^{-1}$)	🟩			
06	Water consumption per sector (m^3 $year^{-1}$)		🟨		
	Regulation and Maintenance				
07	Pollutants removed by vegetation (in leaves, stems and roots) (kg ha^{-1} $year^{-1}$)	🟩			
08	Dry deposition velocity (mm s^{-1})	🟩			
09	Population exposed to high concentrations of pollutants (% of surface area)	🟩			🟥
10	Carbon storage in soil (ton C ha^{-1})	🟩			
11	Carbon sequestration (ton ha^{-1} $year^{-1}$)	🟩			
12	Leaf area index	🟩			
13	Temperature decrease by tree cover (°C m^{-2})	🟩			
14	Cooling capacity of urban green trees	🟩			🟥
15	Cooling capacity of UGI	🟩			🟥
16	Cooling capacity of urban green spaces	🟩			🟥
17	Population exposed to high temperatures (% per unit area)	🟩			🟥
18	Leaf area index + distance to roads (m)	🟩			
19	Noise reduction rates applied to UGI within a defined road buffer dB(A) m^{-2} vegetation unit	🟩			🟥
20	Soil water storage capacity (mm)	🟩			
21	Soil water infiltration capacity (cm)	🟩			
22	Water retention capacity by vegetation and soil (ton km^{-2})	🟩			
23	Intercepted rainfall (m^3 $year^{-1}$)	🟩			
24	Surface run-off (mm)	🟩			
25	Proportion of green areas in zones in danger of floods (%)	🟩	🟨		
26	Population exposed to flood risk (% per unit area)	🟩			🟥
27	Areas exposed to flooding (ha)	🟩	🟨		
28	Capacity of ecosystems to sustain insect pollinators activity (dimensionless)	🟩			
29	Relative abundance (number over area or over a length)	🟩			
	Cultural				
30	Accessibility to public parks, gardens and playgrounds (more than 50 ha)—(inhabitants within 10 km from a park)			🟪	

Code No. (00) for Indicator Framework I	Indicators Adapted from CICES & MAES	Ecology	Socio-Economy (SE)	Socio-Culture (SC)	Human Health (HH)
31	Accessibility to public parks gardens and playgrounds (between 10 ha and 50 ha)—(inhabitants within 1 km from a park)			🟪	
32	Accessibility to public parks gardens and playgrounds (between 2.5 ha and 10 ha)—(inhabitants within 500 m from a park)			🟪	
33	Accessibility to public parks, gardens and playgrounds (between 0.75 ha and 2.5 ha or smaller but important green spaces)—(inhabitants within 250 m from a park)			🟪	
34	Weighted recreation opportunities provided by urban green infrastructure			🟪	
35	Nature-based recreation opportunities (includes Natura 2000; includes bathing water quality) (dimensionless)			🟪	
36	Proximity of green infrastructure to green travel routes (km)			🟪	
37	Green-related social service provided to population (dimensionless)			🟪	
38	Regression models of ES hot spots and cold spots based on georeferenced data (i.e. images or geo tagged locations)			🟪	
39	Accessibility of parks from schools (number of public parks and gardens within a defined distance from a school)			🟪	
40	Cultural and natural heritage sites (e.g. United Nations Educational, Scientific, Cultural Organization (UNESCO) world heritage sites) (number per unit area, % per unit area)			🟪	
In sum	Count	26	5	12	7
	Percentage	52%	10%	24%	14%

Table A. 2 Indicator framework II for GI implementation, from the IEEP, and classified in terms of four dimensions, i.e. ecological (green), socio-economic (yellow), socio-cultural (purple) and human health (red), adapted from Wang et al., 2019a.

Code No.(0000) for Indicator Framework II	GI Functional Indicators	Ecology	Socio-economy (SE)	Socio-culture (SC)	Human Health (HH)
Natural resources					
0001	Forests for wood supply		🟨		
0002	Total area of cropland/grassland suitable for livestock		🟨		
0003	Total area of low input cropland		🟨		
0004	Soil carbon content	🟩			
0005	Species composition, aggregated in functional groups (e.g. biomass of decomposers, proportion of different trophic groups) as an indicator of process capability	🟩			
0006	Abundance and species richness of biological control agents (e.g. predators, insects, etc.)	🟩			
0007	Changes in disease burden as a result of changing ecosystems	🟩			🟥
0008	Range of biological control agents (e.g. in km, regular/aggregated/random, per species)	🟩			
0009	Abundance and species richness of wild pollinators	🟩			
0010	Range of wild pollinators (e.g. in km, regular/aggregated/random, per species)	🟩			
0011	Proximity to natural habitat for pollination	🟩			
0012	Groundwater recharge	🟩	🟨		
0013	Total area of inland water bodies and inland wetlands	🟩			
Water management					
0014	Water infiltration capacity/rate	🟩	🟨		🟥
0015	Water storage capacity in mm/m	🟩	🟨		🟥
0016	Floodplain water storage capacity in mm/m	🟩	🟨		🟥
0017	Water quality in aquatic ecosystems (sediment, turbidity, phosphorous, nutrients, etc.)	🟩			🟥
0018	Biological indicators (e.g. index of biological integrity)	🟩			
0019	Nitrogen retention	🟩			
0020	Nitrogen removal	🟩			
Climate regulation					
0021	Total amount of carbon sequestered/stored=sequestration/storage capacity per hectare * total area ($GtCO_2$)	🟩	🟨		
0022	Evapotranspiration rate	🟩			
0023	Canopy stomatal conductance	🟩			
0024	Wind attenuation potential	🟩	🟨		🟥
Health and well-being					
0025	Atmospheric cleansing capacity in tons of pollutants removed per hectare	🟩			🟥
0026	Downward pollutant flux, calculated as the product of dry deposition velocity and pollutant concentration	🟩			🟥
0027	Reduced stress levels and improving mental health				🟥
0028	Increased physical activities				🟥
0029	Natural sound absorption capacity	🟩			🟥

Code No.(0000) for Indicator Framework II	GI Functional Indicators	Ecology	Socio-economy (SE)	Socio-culture (SC)	Human Health (HH)
	Investment and employment				
0030	Scenery, amenity and environmental quality			🟪	
0031	Employment resulting from GI initiatives		🟨		
0032	Amount of workplace individuals benefiting from GI investment or existing GI		🟨		
	Tourism and recreation				
0033	Scenery, amenity, environmental quality, products, flagship species and habitats		🟨	🟪	
0034	Exercise, scenery, amenity for public recreation			🟪	🟥
	Education				
0035	Educational visits: flagship species and habitats, endemic species			🟪	
	Land and property				
0036	Exercise, scenery, amenity for value uplift (monetary) of individual property			🟪	🟥
	Resilience				
0037	Particular emphasis on regulating and supporting services	🟩	🟨	🟪	🟥
	Conservation benefits				
0038	Existence value of habitat, species and genetic diversity	🟩	🟨	🟪	🟥
0039	Bequest and altruistic value of habitat, species and genetic diversity for future generations	🟩		🟪	
In sum	Count	26	12	7	13
	Percentage	45%	21%	12%	22%

Table A. 3 Indicator framework III for a shift towards a green economy, from the EMDA, classified in terms of four dimensions, i.e. ecological dimension (green), socio-economic dimension (yellow), socio-cultural dimension (purple), and human health (red) dimension, adapted from Wang et al., 2019a.

Code No.(00000) for Indicator Framework III	Indicators for GI Quantitative Benefits	Ecology	Socio-economy (SE)	Socio-culture (SC)	Human Health (HH)
	Natural resources				
00001	Production of food in tons, m^3 and/or hectares		🟨		
00002	Quantity of certified production of food		🟨		
00003	Number of wild species used as food/ornamental resources, etc.	🟩	🟨	🟪	
00004	Employment sustained by agricultural sectors		🟨		
00005	Increased yield attributable to soil quality	🟩			
00006	Increased yield attributable to biological control	🟩			
00007	Increased yield attributable to pollination		🟨		
00008	Population served by renewable water resource	🟩	🟨		
00009	Total annual freshwater consumption by sector	🟩	🟨		
	Water management				
00010	Deprived households at risk of flooding	🟩	🟨		🟥
00011	Reduced surface water run-off	🟩	🟨		🟥
00012	Population served by high water quality	🟩			🟥
	Climate regulation and adaption				
00013	Total amount of carbon removed and contribution to the achievement of climate change targets	🟩	🟨		
00014	Reduced peak summer surface temperatures	🟩			🟥
00015	Building energy savings—heating and cooling	🟩	🟨		🟥
00016	Deprived households at risk of storm damage	🟩	🟨		🟥
00017	Deprived land at risk of storm damage	🟩	🟨		
	Health and well-being				
00018	Total amount of pollutants removed and contribution to air quality targets	🟩			
00019	Human health impact expressed in disability- adjusted life years (daily = years of life lost + years lived with disability)				🟥
00020	Persons/year where defined threshold in dB is not exceeded due to natural sound absorbers	🟩			🟥
	Investment and employment				
00021	Perception surveys on the attractiveness of an area for workers/investors			🟪	
00022	Number of products whose branding relates to cultural identity		🟨	🟪	
00023	Temporary employment impact of GI provision		🟨		
00024	Ongoing employment impact of maintenance		🟨		
00025	Summary of employment sustained by sectors (e.g. agriculture, forestry, tourism and recreation		🟨		
00026	Impact on workers' effectiveness in their jobs		🟨		
	Tourism and recreation				
00027	Employment supported by tourism		🟨	🟪	

Code No.(00000) for Indicator Framework III	Indicators for GI Quantitative Benefits	Ecology	Socio-economy (SE)	Socio-culture (SC)	Human Health (HH)
00028	Amount of nature tourism		🟨	🟪	
00029	Number of visitors to protected sites per year	🟩		🟪	
00030	Number of local users for hiking, camping, nature walks jogging, winter sports, water sports, angling, horse riding, hunting and cycling			🟪	🟥
	Education				
00031	Total number of visits specifically for educational or cultural reasons			🟪	
00032	Total number of educational excursions			🟪	
00033	Number of TV programs, studies, books, etc. featuring sites and the surrounding area			🟪	
	Land and property				
00034	Residential land and property value uplift (1 km from green space)	🟩	🟨	🟪	
00035	Commercial land/property value uplift (1 km from green space)	🟩	🟨	🟪	
	Resilience				
00036	Scoring according to portfolio of services and functions provided	🟩	🟨	🟪	🟥
	Conservation benefits				
00037	Non-use benefits estimated by contingent valuation method or chosen experiment	🟩	🟨	🟪	🟥
n sum	Count	19	23	13	11
	Percentage	29%	35%	20%	17%

Table A. 4 Overview of existing key green infrastructure (GI) definitions and conceptual developments (adapted from Wang and Banzhaf, 2018)

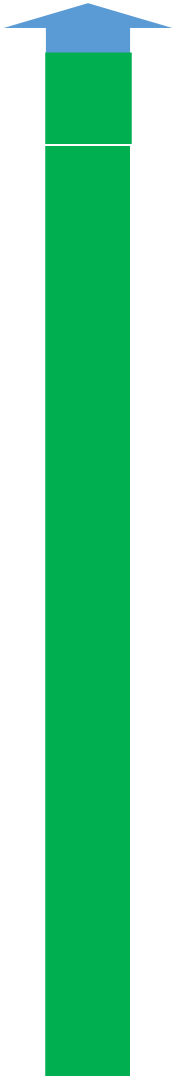
Year	References	Definitions	Key Points and Primary Objectives	Conceptual Development
1999	Towards a Sustainable America - Advancing Prosperity, Opportunity and a Healthy Environment for the 21st Century (The President's Council on Sustainable Development, 1999)	Green infrastructure is defined as: our nation's natural life support system – an interconnected network of protected land and water that supports native species, maintains natural ecological processes, sustains air and water resources and contributes to the health and quality of life for America's communities and people.	Incorporate the human element. The main purpose is to weave nature back into the community in a way that facilitates various levels of human interaction with the environment based upon the resilience of the natural resources being protected. Let natural systems work for people.	Advancing the viewpoint that nature should be brought back into the community
2002	The Conservation Fund's Green Infrastructure Leadership Program (Benedict & McMahon, 2002; 2006)	Green infrastructure is a strategic approach to land conservation, a 'smart' conservation that addresses the ecological and social impact of sprawl and the accelerated consumption and fragmentation of open land (2002). A strategically planned and managed network of natural lands, working landscapes, and other open spaces that conserves ecosystem values and functions and provides associated benefits to human populations (2006).	Land conservation to control urban sprawl	Calling for a balance between eco-centric and anthropocentric approaches
2004	The Conservation Fund, 2004	An interconnected network of wetlands, waterways, woodlands, wildlife habitats, and other natural areas; greenways, parks and other conservation lands; working farms, ranches and forests; and wilderness and other open spaces that support native species, maintain natural ecological processes, sustain air and water resources and	Hubs and links for active and passive recreation, scenic amenity, farmland protection, urban forestry, urban wildlife, regional and state ecological systems, integration of conservation and growth management.	Underlining GI as an approach with the primary objective of identifying suitable lands for conservation in the context of current and future developed lands.

Year	References	Definitions	Key Points and Primary Objectives	Conceptual Development
2005	East Midlands Green Infrastructure Scoping Study: Final Report (2005)	Green infrastructure is a network of multifunctional green spaces provided across the defined area. It is set within, and contributes to, a high-quality natural and built environment and is required to deliver liveability for existing and new communities.	Practice-based definition in the UK	Multifunctional green spaces
2006	Kambites and Owen, 2006, p. 484	Green infrastructure is taken to encompass connected networks of multifunctional, predominantly unbuilt, space that supports both ecological and social activities and processes.	Linking theory and policy	Multifunctional networks
2007	Green Infrastructure for Cities: The Spatial Dimension (Ahern, J., 2007)	Green infrastructure is a concept that is principally structured by a hybrid hydrological/drainage network, complementing and linking relict green areas with built infrastructure that provides ecological functions.	GI concept is aligned with opportunistic strategy by seeking new or innovative opportunities to provide abiotic, biotic, and cultural functions in association with	GI is a movement that aims to change the concept of the ecological network; thus far, this has been focused primarily on maintaining biodiversity and has rarely been applied in urban contexts to urban environments.

Year	References	Definitions	Key Points and Primary Objectives	Conceptual Development
2008	Planning Policy Statement 12: Creating Strong, Safe and Prosperous Communities Through Local Spatial Planning. (Department for Communities and Local Government, 2008)	Green infrastructure is a network of multifunctional green space, both new and existing, both rural and urban, which supports natural and ecological processes and is integral to the health and quality of life of sustainable communities.	As well as enhancing the aesthetics of an area, the same plot of green space can also play a role in improving health, reducing flood risk and boosting the economy. Areas of green infrastructure can be threaded together through the urban environment to provide links between local communities, amenities and the surrounding countryside.	An emphasis should be put on the multifunctionality of green space.
2009	Green Infrastructure: Connected and Multifunctional Landscapes (Landscape Institute Position Statement, 2009)	Green infrastructure is an approach to land use that is underpinned by the concept of ecosystem services. GI assets such as green roofs and walls, city parks, shorelines, national parks are considered in terms of different scales and should not be considered only in relation to their single functions.	The value of natural elements in urban and rural environments, and the economic, social and environmental benefits they provide, is beginning to gain recognition.	Pointing out the concepts of connectivity and multifunctionality, which make GI such an important part of landscape planning and management
2011	Design, Implementation and Cost Elements of Green Infrastructure Projects (European Commission, 2011a)	Green infrastructure is the network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services. Green infrastructure can be strengthened through strategic and coordinated initiatives that focus on maintaining, restoring, improving and connecting existing areas and features as well as creating new areas and features.	Emphasizing the 'life support' functions provided by the natural environment.	Focusing on GI benefits, functions and their links.

Year	References	Definitions	Key Points and Primary Objectives	Conceptual Development
2011	Liverpool City Green Infrastructure Strategy (Mersey Forest Team, 2011)	The city's life support system – the network of natural environmental components and green and blue spaces that lies within and around Liverpool and provides multiple social, economic and environmental benefits.	Multiple benefits	Enhancing the GI concept by means of multiple social, economic and environmental benefits
2013	Enhancing Europe's Natural Capital (European Commission, 2013)	GI is a successfully tested tool for providing ecological, economic and social benefits through natural solutions. It helps us to understand the value of the benefits that nature provides to human society and to mobilize investments to sustain and enhance them. It also helps to avoid reliance on infrastructure that is expensive to build when nature can often provide cheaper, more durable solutions. Many of these create local job opportunities. Green infrastructure is based on the principle that protecting and enhancing nature and natural processes, and the many benefits human society gets from nature, are consciously integrated into spatial planning and territorial development.	It can sometimes offer an alternative, or be complementary to, standard gray solutions.	Emphasizing GI has many benefits when it is compared to single-purpose, gray infrastructure.
2014	Green Infrastructure Life Support for Human Habitats (Ely, M., Pitman, S., 2014)	Green infrastructure is the network of green spaces and water systems that delivers multiple environmental, social and economic values and services to urban communities. This network includes parks and reserves, backyards and gardens, waterways and wetlands, streets and transport corridors, pathways and greenways, farms and orchards, squares and plazas, roof gardens and living walls, sports fields and cemeteries.	Green infrastructure secures the health, liveability and sustainability of urban environments.	It strengthens the resilience of towns and cities in responding to the major current and future challenges of growth, health, climate change and biodiversity loss, as well as water, energy and food security.

Table A. 5 A comprehensive GI typology for AMGI, adapted from Green Surge Milestone 23.

The Gray to Green Continuum	Human Influence/Association with Green Infrastructure (GI)	Class Number	GI Classes	Type Number	GI Types/Ecosystem Service Unit	GI Types analyzed in the AMGI (YES/NO)
	Associated with GI	01	blue spaces			
				001	water course	YES
				002	water body	YES
				003	estuary	NO
				004	delta	NO
				005	sea coast	NO
	Heterogeneous cultivation—biotic	02	arable land			
				006	arable land	YES
				007	bioenergy agriculture/agroforestry	YES
		03	grassland			
				008	pasture	YES
				009	heathland	NO
				010	moorland	YES
		04	orchard			
				011	tree meadow/meadow orchard	YES
				012	horticulture	YES
		05	forest			
				013	managed forest, deciduous and coniferous	YES
				014	woodland (low-density forest forming open habitats)	YES
		06	shrub land			
				015	vegetation dominated by shrubs, including grasses and herbs	YES
	natural, semi-natural areas—biotic	07	Private gardens			
				016	front and backyard garden	NO
		08	River-related green			
				017	riverbank green	YES
		09	Wetlands	018	fen, marsh, bog and wet flush vegetation	YES
		10	parks or public green spaces			
				019	large central park (historical park)	YES
				020	pocket park	YES
				021	botanical garden	YES
				022	zoological garden	YES
				023	neighborhood green space	YES
				024	institutional green space	NO
				025	cemetery and churchyard	YES
				026	sport and leisure facility	YES

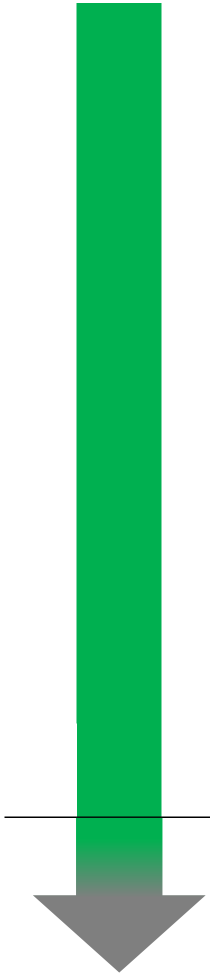
The Gray to Green Continuum	Human Influence/Association with Green Infrastructure (GI)	Class Number	GI Classes	Type Number	GI Types/Ecosystem Service Unit	GI Types analyzed in the AMGI (YES/NO)
				027	campsite	YES
		11	allotments and community gardens			
				028	community garden (tended collectively by a group of people on private or public land)	YES
				029	allotment (small plots for individuals which collectively make up a larger green space)	YES
	Man-made biotic close to gray infrastructure	12	building greens			
				030	balcony green	NO
				031	ground-based green wall	NO
				032	façade-bound green wall	NO
				033	extensive green roof	NO
				034	intensive green roof	NO
				035	atrium	NO
		13	commercial, industrial, institutional urban green space (UGS) and UGS connected to gray infrastructure			
				036	bioswale	NO
				037	rain garden	YES
				038	railroad bank	NO
				039	playground, school grounds	YES
				040	ruderal area	YES
		14	Street trees			
				041	tree alley, street tree, aligned hedge	YES
	natural, semi-natural areas—abiotic	15	Natural abiotic surface			
				042	rock	NO
				043	sand dune	NO
	Not GI	16	Human-induced abiotic surface			
				044	sealed surface, impervious surface, built-up area	NO
				045	derelict land/abandoned area	NO
				046	sand pit, quarry, open cast mine	NO

Table A. 6 Types of GI mapping approach and their respective multiple functions at different scales (adapted from Wang and Banzhaf, 2018))

Types of GI mapping approach	References and types of GI function	Scale	Each mapping approach as fraction [%]
GI using the Urban Atlas	(Larondelle et al., 2014): 8/9	urban	2.99
	(Madureira & Andresen, 2014): 9/12	urban	
GI using CORINE Land Cover, or combination of Natura 2000 and some other land-use and -cover datasets	(Wan-yu Shih, 2009): 12/18/23/25/26;	urban	10.45
	(Baur, A. H., M. Forster, et al., 2015): 9	national	
	(Derkzen et al., 2015): 18/11/9/8/6/13	neighborhood	
	(Soukup et al., 2016): -	international	
	(Stueve et al., 2015): -	sub-regional	
	(Van der Zanden et al., 2013): -	continental	
	(McWilliam et al., 2015): -	urban	
GI and landscape fragmentation models	(Allen III, W.L., 2014.):-	sub-regional	5.97
	(Barredo, J. I., G. Caudullo et al., 2016): 9/25	sub-regional	
	(Patru-Stupariu et al., 2013): 3/25	sub-regional	
	(Petropoulos et al., 2015): -	urban	
GI and net landscape ecological potential	(Liu et al., 2014a): -	local	2.99
	(Bell, G., S. Neal & K. Medcalf, 2015): 9/25	local	
GI using morphological spatial pattern analysis (MSPA)	(Kang & Kim, 2015): -	urban	5.97
	(Ramos-Gonzalez, 2014): -	urban	
	(Poll et al., 2016): 3	sub-regional	
	(Wickham et al., 2010): -	national	
GI and mapping of ecological corridors	(Camino Liquete et al., 2015): 2/4/5/6/7/9	continental	10.45
	(Capotorti et al., 2015): 6/23/24	local	
	(Amichev, B. Y. et al., 2015):1/2	sub-regional	
	(Harrison et al., 2016): -	sub-regional	
	(Hunter & Brown, 2012): -	urban	
	(Snall et al., 2016): 26	continental	
	(Teng et al., 2011): 6/18	urban	
GI and Corine ecotones or protected areas	(Fischer et al., 2013): 14/25	urban	4.48
	(Hou & Walz, 2014): -	sub-regional	
	(Kuttner et al., 2014): -	sub-regional	
GI mapping within Quickscan GI, integrated Geographical	(TMF, 2010): -	urban	38.81
	(Norton et al., 2015): 9	urban	
	(Weber et al., 2006): 5/6	sub-regional	
	(Birkenholtz, T., 2013): 5	neighborhood	
	(Bodurow, C. C., 2009): -	neighborhood	

Types of GI mapping approach	References and types of GI function	Scale	Each mapping approach as fraction [%]
Information System tools or other tools	(Charlesworth et al., 2016): 6/7	sub-regional	
	(Green et al., 2015): 5	international	
	(Haybatollahi et al., 2015): 12/17	neighborhood	
	(Hepcan, C., 2013a): -	sub-regional	
	(Hepcan, S., 2013b): -	sub-regional	
	(Jim & Chan, 2016): -	urban	
	(Kremer et al., 2016): 6/8/9/11/18	urban	
	(Miralles I. Garcia & Grau, 2016): -	sub-regional	
	(Raymond et al., 2016): -	sub-regional	
	(Schmidt et al., 2014): 6	sub-regional	
	(Siedentop et al., 2016): -	sub-regional	
	(Sisman & Bolu, 2015): 18/20	sub-regional	
	(Taylor & Lovell, 2012): -	urban	
	(Tillie & van der Heijden, 2016): 6/18	urban	
	(Voigt et al., 2014): 18	local	
	(Vollmer & Gret-Regamey, 2013): 5/6/7/26	neighborhood	
	(Weber et al., 2008): 3	urban	
	(Wheeler, 2015): -	international	
	(Davis et al., 2012): 3/26	urban	
	(Liu et al., 2014b): -	sub-regional	
	(Kopperoinen et al., 2014): 1/2/3/4/5/6/7/8/9/11/12/18/19/20/27	sub-regional	
GI using regional environmental characterization or integrated modeling tools	(Freeland et al., 2014): -	urban	17.91
	(Gill et al., 2008): 6/9	urban	
	(Jorgensen & Gobster, 2010): -	urban	
	(Isely et al., 2010): 1/2/4/5/6/7/12/18	sub-regional	
	(Kati & Jari, 2016): 21/22/25	local	
	(Qureshi et al., 2010): 12	urban	
	(Waltham & Sheaves, 2015): 1	sub-regional	
	(Watson et al., 2016): 5/6	sub-regional	
	(Verlic et al., 2014): -	sub-regional	
	(Barau, A. S., 2015): 1/12	sub-regional	
	(Natural England, 2009): 12/14/26	sub-regional	
	(Mubareka et al., 2013): 1/6	continental	

(The "/" means "and", "-" means "no GI functional analysis involved in a particular publication").

Table A. 7 A lean indicator framework to exemplify AMGI (adapted and selected from the integrated framework from Wang et al., 2019a)

Indicator & unit	**Database**	**Data type**	**Method/Source**	**Values**
Average Carbon storage [MgC/ha]	Biotope mapping	Polygon	Analysis and extraction from Strohbach and Haase (2012), Derkzen et al. (2015) and Schröder et al. (2013)	11.80
Community gardens/allotments for food self-supply per inhabitant [m^2/inh.]	Biotope mapping	Polygon	Calculation and aggregation*	28.20
Proportion of water surface [%]	Local land-use and -cover map	Polygon	Calculation and aggregation*	2.50
Proportion of wetlands for water regulation [%]	Biotope mapping	Polygon	Calculation and aggregation*	0.04
Vegetation areas alongside water courses for water regulation [ha]	Biotope mapping	Polygon	Identification and calculation	0.14
Proportion of green areas in municipal districts in danger of floods [%]	Biotope mapping	Polygon	Calculation and aggregation	56.65
Proportion of areas of municipal districts potentially exposed to urban flooding [%]	Biotope mapping	Polygon	Calculation and aggregation	42.83
Cooling effects of GI compared to sealed surfaces [°C/m^2]	Urban Atlas	Raster	Analysis and extraction from Schwarz et al. (2012)	0.25
Recreation spaces per inhabitant [m^2/inh.]	Biotope mapping	Polygon	Calculation and aggregation*	69.51
Total area of urban alluvial forests for habitat, species and genetic diversity [ha]	Biotope mapping	Polygon	Identification and calculation*	1,033.00
Areas exposed to extreme flood risk [km^2]	Local case study	-	Data from Kubal et al. (2009)	45.00
Proportion of areas exposed to flooding [%]	Local case study	Polygon	Data from Kubal et al. (2009)	8.00
Proportion of population exposed to flood risk	Biotope mapping	Polygon	Calculation and aggregation	46.18
Population without urban green spaces in their neighborhood [%]	Urban Atlas	Polygon	Method newly introduced by Poelman (2018),	2.37

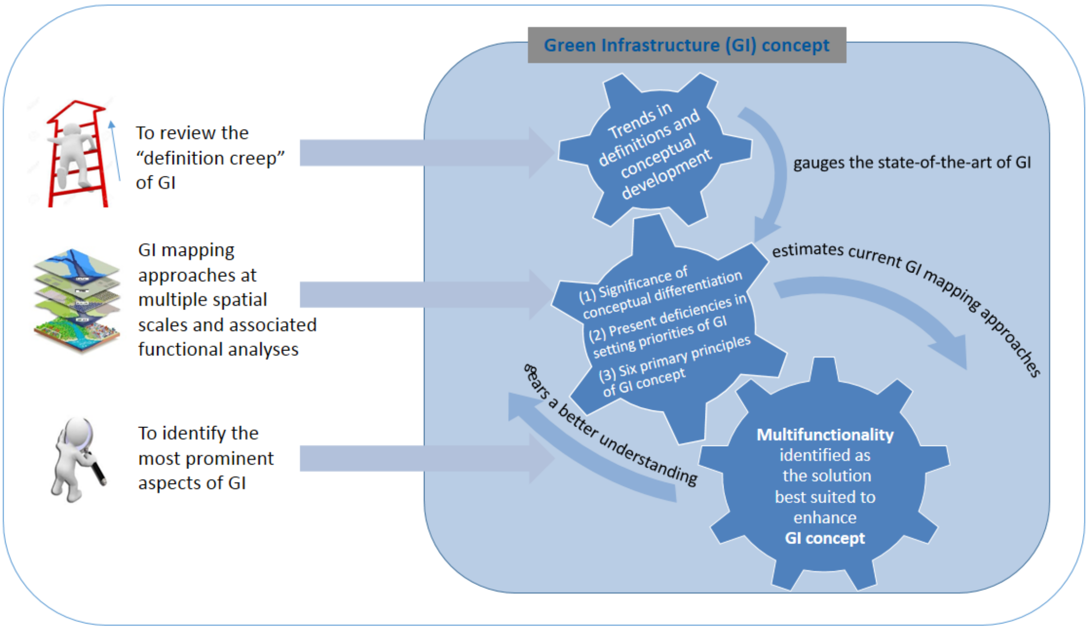
Indicator & unit	Database	Data type	Method/Source	Values
Increased physical activities in GI areas	Field surveys	Point	Observation and survey	N/A
Employment in directly GI-related sectors (agriculture, forestry and fisheries [%])	Sachsen Statistics (Statistisches Landesamt Sachsen, 2012)	-	Statistik der Bundesagentur für Arbeit (Juni 2014.)	13.70
Residential land and property increment value (1km from green areas)	Wohnungsbörse Leipzig (Wohnungsbörse Leipzig, 2019)	-	Stadt Leipzig Sozialamt (2016)	N/A
Total number of visits specifically for educational or cultural reasons [inh.]	Statistics	-	Stadt Leipzig Sozialamt (2016)	N/A

*) this indicator was adapted and further used for GI function mapping to identify the spatial distribution of hot spots of GI functions.

Appendix: Research papers

Paper I

Wang, J., Banzhaf, E., 2018. Towards a Better Understanding of Green Infrastructure: A Critical Review. *Ecological Indicators*. 85, 758–772. https://doi.org/10.1016/j.ecolind.2017.09.018.



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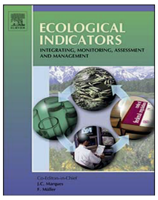

Review article

Towards a better understanding of Green Infrastructure: A critical review

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ABSTRACT

Based on a comprehensive analysis of key definitions of Green Infrastructure (GI) and their conceptual evolution, we present a review of current GI mapping approaches at multiple spatial scales and their associated functional analyses. GI is an approach that is used to combine ecosystem services and human well-being to realize an efficient and sustainable use of spaces, hereafter named “GI concept”. The interdisciplinary database that forms the basis of our literature review includes peer-reviewed journal papers as well as books and documents published by international organizations, governmental agencies, and research institutions. By analyzing these publications – not only English but also Chinese articles – we present an exhaustive review that gauges the state and evolution of GI in chronological terms, and we discuss how GI should be further improved. We systematically examine what GI actually measures and question whether its current manifestations are consistent with its conceptual development. Furthermore, we seek to find out whether there are specific trends in the conceptual evolution of definitions of GI, and whether there are gaps between this evolution and the implementation of GI in the context of advancing sustainable development. We then draw attention to differentiation while analyzing GI functions and classifications. On this foundation, we discuss six primary principles and propose a number of ways of enhancing and applying GI in the future. Our review shows that, at this point in time, special emphasis on the core idea of multifunctionality is significant for depicting the ‘state of the art’ of the evolving GI concept. Finally, the study identifies multifunctionality as the solution best suited to enhance the GI concept and to open up potential avenues for further research.

1. Introduction

Green infrastructure (hereafter GI) has been identified as one of several key strategies for achieving sustainability. GI is regarded as beneficial because it can provide habitats for various biota and thereby protect terrestrial and aquatic ecosystems (Demuzere et al., 2014; EEA, 2011; Ignatieva et al., 2011). Both GI and ecosystem services (ESS) have been widely promoted as suitable strategies for improving environmental planning in relation to different spatial scales. The potential of GI and ESS is rooted in a holistic understanding of social, ecological and physical systems. GI was first introduced in the mid-1990s (Pauleit et al., 2011) and has since become part of the sustainability discourse used by a wide range of agencies, organizations, companies, community groups, and planners. This concept offers practical ways of dealing with the rising rate of land consumption and fragmentation at various scales, while enhancing interdisciplinary collaboration and information sharing at different levels and offering the potential to achieve sustainable development and a fair quality of life (Soule, 1991; Margules and Pressey, 2000; Conservation Measures Partnership, 2004, 2013; McDonald et al., 2005; EEA, 2015). By reviewing the literature about the GI concept, we hope in the first instance to prompt planners to consider GI as a strategic approach to conservation and development that helps to drive environmental planning and land preservation towards sustainable development.

In addition, the concept should be examined in terms of its theoretical evolution in order to find out whether there are any major trends in it that point towards more efficient ways of implementing GI since the concept was first put forward (Mazza et al., 2011). To give an example of this, GI has been defined by The Conservation Fund (2004) as the interconnected network of natural and semi-natural areas, features and green spaces that support native species, maintain natural ecological processes in rural and urban areas, and contribute to the health and quality of life for human beings (The Conservation Fund, 2004). Two years after its first delineation The Conservation Fund updated their definition as “a strategically planned and managed network of natural lands, working landscapes, and other open spaces that conserves ecosystem values and functions and provides associated benefits to human populations, in order to link GI concept closely to its

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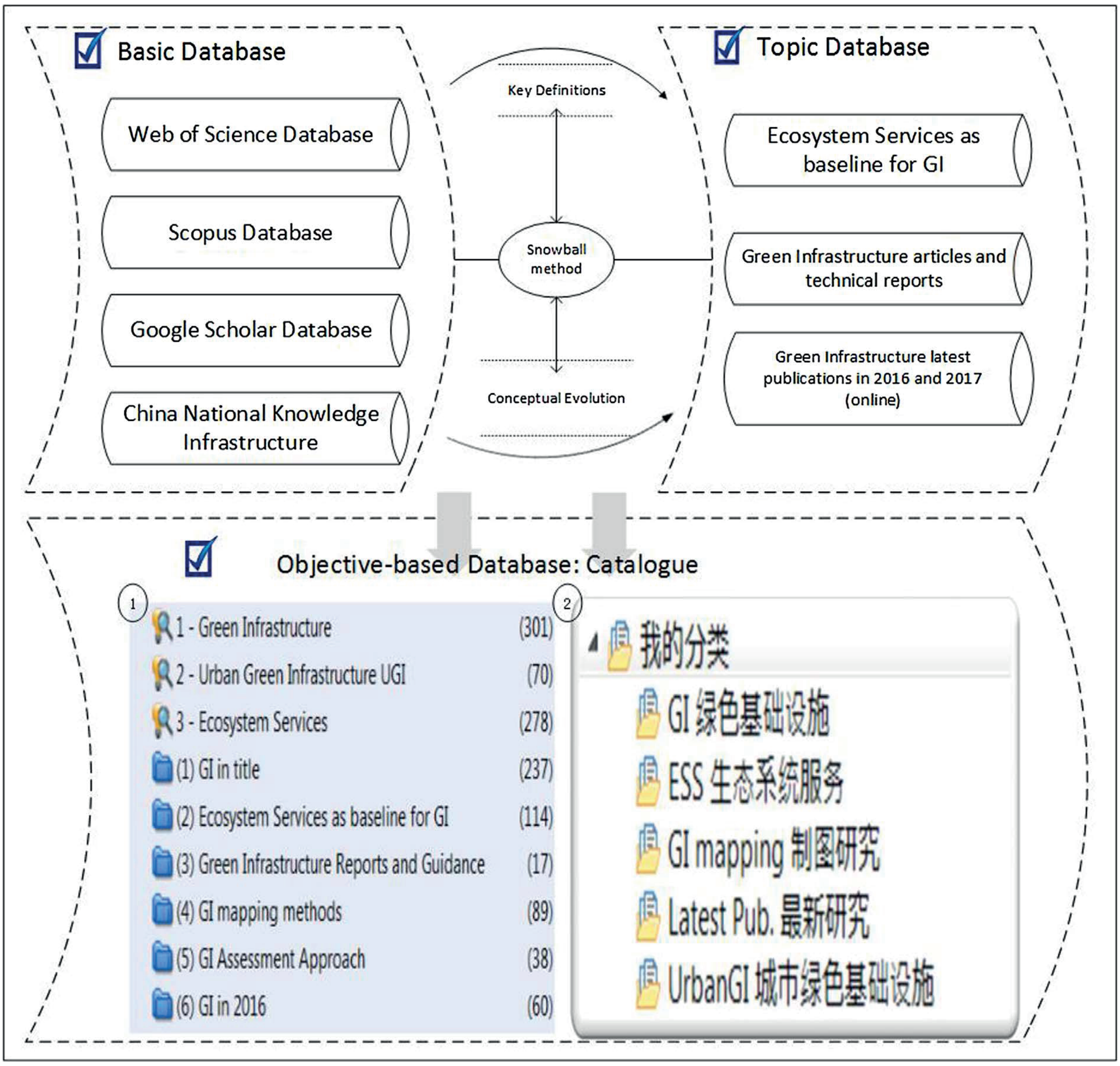


Fig. 1. Entire database management for basic, topical and objective-based catalogues.

implementation" (Benedict and McMahon 2006, p. 7). The natural features of this broad concept were not merely restricted to features that support native species i.e. GI definition in the year of 2004, but they include parks, forest reserves, terrestrial, freshwater, coastal and marine areas, as well as man-made elements, such as ecoducts and cycle paths (Naumann et al., 2011a, 2011b; European Commission, 2013). The range and extent of GI means it can perform several functions at several scales while simultaneously taking into account the multiple connections and interactions which are so essential in nature. It is for this reason that, in scientific debates, GI has often been described in terms of policy (Naumann et al., 2011b). The European working group 'Science for Environment Policy' has, for instance, strongly supported GI as a policy goal because it has the potential to offer 'win–win' or 'no-regret' solutions. Furthermore, the group asserts, it could promote integrated spatial planning by identifying multi-functional zones and incorporating habitat restoration measures into land use plans and policies (EC, 2012; EU, 2013). GI can also be a highly valuable policy tool to promote sustainable development and smart growth by meeting multiple objectives and addressing various demands and pressures (EEA, 2011). However, a broader approach to GI highlights the need for a holistic review of GI functions, from nature conservation to the social benefits provided for residents at regional, urban and local, site-specific scales (Naumann et al., 2011a,b; Niemelä et al., 2010; Pauleit et al., 2011; Demuzere et al., 2014). Improved knowledge of the scales at which functions and benefits are provided for residents should be used to link the conceptual development of GI to appropriate levels of decision-making and implementation, whether continental or national, sub-regional or local (Sternlieb et al., 2013; Wyborn and Bixler, 2013). We find this issue to be in accordance with the synergy across boundaries (multi-scale integrated analysis) in the Sustainability Impact Assessment (SIA). Dealing with the complexity of interactions between different land uses, these reflections are also based on SIA which regards temporal and spatial scales, and the respective steering policies (Pérez-Soba et al., 2008).

Since its early days, GI has been defined in many different ways. We therefore need an exhaustive review of the development of the concept in order to capture its essence and achieve a better understanding and more effective implementation. A systematic review of GI, including the approaches necessary for GI mapping to support the planning process, has been lacking to date (Liquete et al., 2015). This study aims at defining the term Green Infrastructure (GI) from a possible complete bibliographical revision.

Therefore, our goal in the review is to find answers to the following three specific questions: Q1) How has the concept of GI evolved over time and what elements of that evolution should be extracted for further use? Q2) What are current GI mapping approaches, and how do they fit alongside the conceptual evolution of GI? Q3) How can a combination of qualitative and quantitative information be used to better understand GI based on GI multifunctionality? Q1 to Q3 are geared towards the following objectives:

i To review and carefully scrutinize the state of the art of the conceptual evolution of GI and understand the 'definition creep' of GI as a concept.
ii To review existing GI mapping approaches and tools in terms of different spatial scales and multiple functions of GI.
iii To identify the most prominent aspects of GI which are capable of steering it in a more efficient direction in future.

2. Materials and methods

To make this literature review as integrative and exhaustive as possible, a wide range of relevant sources were examined to find meta-analyses of published scientific papers. Up to October 31, 2016, we searched the following data bases for full journal and peer-reviewed articles as well as technical reports and guidance using a large range of search terms and Boolean operators (e.g. Urban AND green infrastructure AND multifunctional OR assessment, green spaces AND multifunctional etc.) and setting the search timespan as all years: 1) Web of Science database; 2) Scopus; 3) Google Scholar database; and 4) China National Knowledge Infrastructure (CNKI). Fig. 1 illustrates our database structure, designed to meet our research objectives (i), (ii) and (iii).

English is the principal language of international academic publications (e.g. Ziter, 2016; Alavipanah et al., 2017) and our major reference. One novel – and necessary – aspect is that our review includes Chinese research results. Publications of Chinese research are important to be illuminated because Chinese urbanization and related ecological pressure is globally unprecedented. In most reviews undertaken so far, Chinese publications have been understood to be useful on the basis of their abstracts (many articles published in key Chinese journals have English abstracts but are otherwise written in Chinese) and have been included from 1975 onwards (Haase et al., 2014; Alavipanah et al., 2017). As the actual studies of these Chinese articles are not published in English, they could not be included for further detailed analysis by the above-referenced authors. Therefore some Chinese research in GI (e.g. the China Sponge city concept and Turenscape GI design) is considered to be an innovative and proactive response. An urban planning instrument such as Taizhou city plan (2006) designed by Landscape Architect Kongjian Yu and a research team at Peking University, multifunctional GI planning research in Haidian District, Beijing conducted by Prof. Yu's research team (2013) at China Agricultural University (Liu et al., 2014), all serve to elucidate GI guidelines with respect to connectivity and multi-purpose water systems (Ahern, 2007).

The global search covered the topic area (Fig. 1 topic database) of GI and returned more than 467 unique records. The title of each paper and the executive summary of each report were first carefully checked for relevance to 1) the GI concept and 2) the GI mapping approach on the basis of their abstracts. A large number of publications (114) on Ecosystem Services (ESS) assessment were deliberately included in this review database to provide a robust basis for considering mapping tools with potential relevance for GI.

Overall, out of a total of 440 articles, 139 studies had to be discarded, leaving 301 articles to be included in our in-depth analyses. Our database of this review on GI research publications is run by two software packages, namely, Endnote X7.1 and CNKI E-learning 2.1 (see the catalogue of our review database in Fig. 1).

A 'snowball method' of literature review was conducted, starting with the reference lists of key articles and documents (Mouton and Babbie, 2001). Where key documents cited other literature, the original source of information was acquired and reviewed. Literature referenced in the reviewed papers was added to this GI research database. For example, some ESS can be provided by GI, and so we included the related ESS publications and filtered them carefully according to their forms and services (Fig. 1).

3. Key definitions and conceptual evolutions of GI

GI provides a conceptual framework that allows to attain a better balance amid the ever-growing conflicts between and changes in man-made infrastructure and natural ecosystems. The man-made infrastructure (also known as "gray infrastructure") has been described as the functional support system of urbanized areas. It has impeded natural processes that involve the migration of animals, the flow and filtration of water, the food chain, and plant succession etc. (Benedict and Bjornland, 2002). This gray, or built, infrastructure is usually a standard solution designed to provide humans with specific services; it typically fulfills only single functions, such as drainage or transport (Liquete et al., 2015). In contrast to this, GI has been rapidly introduced in both planning theory and policy (Lennon, 2015).

In its May 1999 report, "Towards a Sustainable America – Advancing prosperity, opportunity and a healthy environment for the 21st Century", the US President's Council on Sustainable Development initiated efforts to identify and apply concepts of GI to the goal of future sustainable development. Following on from this, The Conservation Fund defined GI as America's natural life support system (The Conservation Fund 2004). In a recent European Commission communication (2013), GI was defined as a "strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services". Regardless of whether the definitions of GI stem from the US or the EU, they consistently contain natural and human-made components as fundamental elements. Nonetheless, we have identified no single widely recognized definition of GI in the literature reviewed to date.

In general, the issue of how to define GI is the first one mentioned in both academic articles and planning guidance. Definitions are therefore a useful starting point for analysis, carrying significant authority and to some degree expressing the values that are attached to the concept (Wright, 2011). In the Technical Report on GI and Territorial Cohesion (EEA, 2011, p. 30), it is suggested that GI has been adopted by the various design, conservation and planning-related disciplines (EEA, 2011). But this does not mean that GI can be used without a specific definition. Indeed, research on GI might even be hindered by those broad definitions (Van der Windt and Swart, 2008). Based upon the articles that drew up list of GI definitions previously used by several institutions and publications (e.g. Sylwester, 2009; Kambites and Owen, 2006; EEA, 2011), we provide a detailed overview over existing key GI definitions (Table A1), constructed on the basis of an analysis of their key points, primary objectives and positions within the development of GI concept since it was first put forward.

Based on the information contained in Table A1, we draw the timeline of GI conceptual development and its specific developmental points illustrated in Fig. 2. Both of them help us to disclose the trends in the concept's development by gaining insight into its evolution.

According to the conceptual evolution of GI (see Fig. 2 and Table A1), we can compile three mainstream understandings of GI, incorporating their primary transferring processes:

1) Translation of the relationship between natural systems and human beings: bringing nature back into the human community to realize a balance between eco-centric and anthropocentric approaches (The President's Council on Sustainable Development, 1999; Benedict and McMahon, 2002).

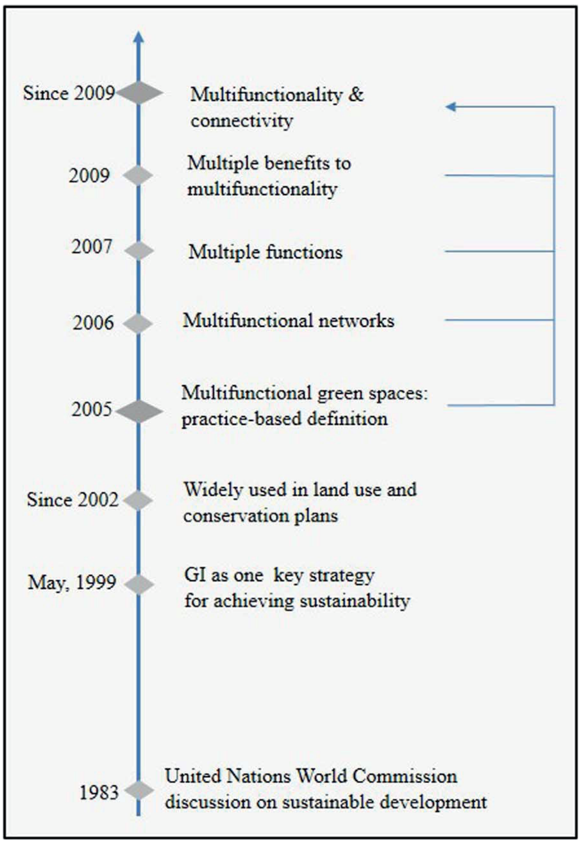


Fig. 2. Timeline for the conceptual evolution of Green Infrastructure (milestones are marked with larger, darker icons).

2) Translation of the former GI advocacy approach into further research that asks 'to what extent can GI work as a practical measure?' This question makes us aware that it is still a challenge how this process might be carried out. When linking theory and policy in order to push GI to the forefront of policy, a best practice is England. There it took just two years for GI to progress from a reference in planning policy (DCLG, 2008) to the basis of emerging national policy (TEP, 2005; Kambites and Owen, 2006; DCLG, 2007, 2008, 2010b; EMDA, 2010, etc.). This kind of semantic translation is usually an arena of political contestation over how the concept is operationalized (TEP, 2005, 2008; DCLG, 2010a, 2010b).
3) Translation of the definition of GI and GI research into an understanding of its multifunctionality. This aspect gets a rising attention, even though various definitions have been widely developed and used in land use and conservation plans. In this case, the focus is on multifunctional networks, multiple functions, multiple benefits etc. by enhancing GI and implementing its multifunctional properties. It may also, however, stem from the fact that multifunctionality, i.e. the ability to provide several functions and benefits on the same spatial scale, is one key attraction of GI (EC, 2012; EEA, 2014). Significant evidence of this trend is provided by the 47 articles found from a specific literature search in the ISI Web of Science and Scopus to identify studies of multifunctional GI, 60% of which (28/47) were published as recent as in 2016. One article notes that the elements of connectivity and multifunctionality make GI an important part of landscape planning and management (Landscape Institute, 2009). Thus we conclude an increasing need to address the multifunctional aspect of GI.

In sum, the key definitions and the conceptual evolution of GI analyzed above incorporate three main trends of research aimed at achieving a better understanding of GI along with three primary translation processes. Nonetheless the intrinsic complexity of GI definition (Table A1), stakeholders can understand the significance of GI as such. When applying specific GI into planning, the concept of multifunctionality is more tangible than "sustainability", even though both share the goal of creating more resilient cities.

4. Critical review of existing GI mapping approaches and GI function analysis

4.1. Literature review from publications in English

Currently no consensus or single mapping method for GI exists in literature that could explain which GI mapping method would be best to use for a specific purpose and under specific conditions. Several factors including scientific objectives, data availability, characteristics of the study area, availability of resources and corresponding policy background might determine the choice of approach and tools (EEA, 2011; Schägner et al., 2013). In our opinion, GI mapping provides a strong evidence base which can ultimately facilitate the development of recommendations on how to manage regional GI assets in order to improve GI functionality. This, again, is relevant for adequately addressing the needs of inhabitants and natural systems (North West Unit, 2008). When refining our literature search in the effort to find an answer to our second question (objective ii, Section 1), we were able to identify 88 publications that deal with GI mapping at multiple scales. Having made this selection, however, we discovered that further clarification is needed to prove the relevance of these data sets in terms of a close relation between GI mapping and the underlying concept of GI. For example, the article published by Baptiste et al. (2015) contains the prominent search keywords "Green Infrastructure"; "GI implementation"; "GI functions"; "GI map"; "GI measurement"; and "GI neighborhood scale map". However; the authors discuss "a targeted approach to implement GI involving neighborhood willingness" (Baptiste et al., 2015, pp. 5–11); which is not closely related to research on the GI mapping approach.

As shown by the qualitative approach in Section 3, our GI mapping analysis is guided by multiple functions of GI. In order to undertake a critical review, we had to cut down the number of relevant articles from the whole database described in Section 2. As a result, we found 67 publications (n = 67) which give profound support for GI implementation and possible future assessment. Each publication was carefully scrutinized by scanning the key concerns 1) to 3) as follows:

i The involved types of GI mapping approach. Our findings show the typology of GI mapping approaches and tools widely employed (Dan, 2012; EEA, 2011; Lovell and Taylor, 2013; Maes et al., 2013; Schägner et al., 2013; EEA, 2014): GI using the Urban Atlas; GI using CORINE Land Cover, or a combination of Natura 2000 and other Land Use and Land Cover (LULC) datasets; GI and landscape fragmentation models; GI and Net Landscape Ecological Potential (NLEP); GI using Morphological Spatial Pattern Analysis (MSPA); GI and mapping of ecological corridors; GI and CORINE, especially ecotones or protected areas; GI mapping by means of the Quickscan software module, integrated Geographical Information System (GIS) or other tools; GI using regional environmental characterization or integrated modeling tools. As an outcome, these approaches are complementary and provide information from more than one input data source, e.g. fragmentation (EEA, 2014), land use and land cover (Urban Atlas), coordination of information on the environment (spatial analysis) etc.

ii Scale of the conducted mapping. We could extract continental (including pan-European), international, national, sub-regional, urban, and local (including sites, neighborhood, and community) scale.

iii Types of analyzed GI functions. We found that GI functions are classified manifold such as by Naumann et al. (2011b) and in the Liverpool GI strategy (TMF, 2010, 2013): 1) capacity to provide a

Table 1

Types of GI mapping approach and their respective multiple functions at different scales (The "/" means "and", where there is no GI functional analysis involved in a particular publication, we use "-" as indication.). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article).

Types of GI mapping approach	**References and type of GI functions**	**Scale**	**Each mapping approach as fraction [%]**
GI using the Urban Atlas	(Larondelle et al., 2014): 8/9	urban	2.99
	(Madureira & Andresen, 2014): 9/12	urban	
GI using CORINE Land Cover, or combination of Natura 2000 and some other Land Use and Cover datasets	(Shih, W.Y. et al., 2009): 12/18/23/25/26;	urban	10.45
	(Baur, A. H., M. Forster, et al., 2015): 9	national	
	(Derkzen et al., 2015): 18/11/9/8/6/13	neighborhood	
	(Soukup et al., 2016): -	international	
	(Stueve et al., 2015): -	sub-regional	
	(Van der Zanden et al., 2013): -	continental	
	(McWilliam et al., 2015): -	urban	
GI and Landscape fragmentation models	(Allen III, W.L., 2014.):-	sub-regional	5.97
	(Barredo, J. I., G. Caudullo et al., 2016): 9/25	sub-regional	
	(Patru-Stupariu et al., 2013): 3/25	sub-regional	
	(Petropoulos et al., 2015): -	urban	
GI and Net Landscape Ecological Potential	(Liu et al., 2014a): -	local	2.99
	(Bell, G., S. Neal & K. Medcalf, 2015): 9/25	local	
GI using Morphological Spatial Pattern Analysis (MSPA)	(Kang & Kim, 2015): -	urban	5.97
	(Ramos-Gonzalez, 2014): -	urban	
	(Poll et al., 2016): 3	sub-regional	
	(Wickham et al., 2010): -	national	
GI and Mapping of ecological corridors	(Liquete, C. et al., 2015): 2/4/5/6/7/9	continental	10.45
	(Capotorti et al., 2015): 6/23/24	local	
	(Amichev, B. Y. et al., 2015):1/2	sub-regional	
	(Harrison et al., 2016): -	sub-regional	
	(Hunter & Brown, 2012): -	urban	
	(Snäll et al., 2016): 26	continental	
	(Teng et al., 2011): 6/18	urban	
GI and Corine ecotones or protected areas	(Fischer et al., 2013): 14/25	urban	4.48
	(Hou & Walz, 2014): -	sub-regional	
	(Kuttner et al., 2014): -	sub-regional	
GI mapping within Quickscan GI, integrated Geographical Information System tools or other tools	(TMF, 2010): -	urban	38.81
	(Norton et al., 2015): 9	urban	
	(Weber et al., 2006): 5/6	sub-regional	
	(Birkenholtz, T., 2013): 5	neighborhood	
	(Bodurow, C. C., 2009): -	neighborhood	
	(Charlesworth et al., 2016): 6/7	sub-regional	
	(Green et al., 2015): 5	international	
	(Haybatollahi et al., 2015): 12/17	neighborhood	
	(Hepcan,C., 2013a): -	sub-regional	
	(Hepcan, S., 2013b): -	sub-regional	
	(Jim & Chan, 2016): -	urban	

(*continued on next page*)

Table 1 (*continued*)

	(Kremer et al., 2016): 6/8/9/11/18	urban	
	(Miralles I. Garcia & Grau, 2016): -	sub-regional	
	(Raymond et al., 2016): -	sub-regional	
	(Schmidt et al., 2014): 6	sub-regional	
	(Siedentop et al., 2016): -	sub-regional	
	(Sisman & Bolu, 2015): 18/20	sub-regional	
	(Taylor & Lovell, 2012): -	urban	
	(Tillie & van der Heijden, 2016): 6/18	urban	
	(Voigt et al., 2014): 18	local	
	(Vollmer & Gret-Regamey, 2013): 5/6/7/26	neighborhood	
	(Weber et al., 2008): 3	urban	
	(Wheeler, 2015): -	international	
	(Davis et al., 2012): 3/26	urban	
	(Liu et al., 2014b): -	sub-regional	
	(Kopperoinen et al., 2014): 1/2/3/4/5/6/7/8/9/11/12/18/19/20/27	sub-regional	
GI using regional environmental characterization or integrated modeling tools	(Freeland et al., 2014): -	urban	17.91
	(Gill et al., 2008): 6/9	urban	
	(Jorgensen & Gobster, 2010): -	urban	
	(Isely et al., 2010): 1/2/4/5/6/7/12/18	sub-regional	
	(Kati & Jari, 2016): 21/22/25	local	
	(Qureshi et al., 2010): 12	urban	
	(Waltham & Sheaves, 2015): 1	sub-regional	
	(Watson et al., 2016): 5/6	sub-regional	
	(Verlic et al., 2014): -	sub-regional	
	(Barau, A. S., 2015): 1/12	sub-regional	
	(Natural England and Landuse Consultants, 2009): 12/14/26	sub-regional	
	(Mubareka et al., 2013): 1/6	continental	

Online version: color red means relatively rare mapping approach; color green means current major GI mapping tools – the darker green hue points at more prevalent tools.
Print version: the broader the columnar the higher the fraction of each mapping approach.

diversified portfolio of products; 2) maintenance of soil fertility; 3) biological control; 4) pollination; 5) storage of freshwater resources; 6) regulation of water flows; 7) water purification; 8) carbon storage and sequestration; 9) temperature control; 10) storm damage control; 11) air quality; 12) accessibility for exercise and amenity; 13) noise regulation; 14) image enhancement; 15) investment and employment; 16) labor productivity; 17) tourism; 18) recreation; 19) research; 20) education; 21) land; 22) property; 23) resilience ecosystem services; 24) emphasis on regulating and supporting services; 25) existence value of habitat; 26) existence value of species; 27) existence value of genetic diversity; 28) listing the significant historical differences.

Table 1 summarizes the results from all the relevant articles that fulfil these criteria and the calculated fraction of the quantitative use of each mapping approach. Furthermore, our results show that GI mapping methods which use GIS and integrated modeling tools are the most widely used approaches (56.72%). With reference to GI using integrated GIS tools (Table 1), we chose typology mapping in the North West Regional Spatial Strategy in England (NWRSS) as an in-depth case analysis and as a typical GI mapping approach. The current NWRSS approach has not attempted to make a link between GI classes and the functions/benefits of GI, but a great many studies manifest the significance of this linkage for GI implementation and efficiency (EEA, 2011; Mazza et al., 2011). Likewise, Liverpool City Region GI Framework and GI Strategy identifies benefits that result directly from particular functions, while benefits that only result indirectly from particular functions via a longer chain are ignored (Natural England, 2009). We want to note, however, that this mapping of benefits is arguably misleading, due to the arbitrary way in which the benefit groups have been divided into 28 functions. The process of analysis does not deliver any explicit information, especially in GI strategy version 1.0 (2010). For this reason, we do not recommend referring to an intervention plan.

To highlight one type of functional mapping as a way of providing an insight into GI, Morphological Spatial Pattern Analysis (MSPA), which accounts for about 6% in this review (see Table 1) based on mathematical morphology (Soille, 2013), identifies hubs and links from a single land-cover map rather than overlaying several maps in a GIS. In doing so, it distinguishes structure from the spatial relationships existing among different land-cover features (Wickham et al., 2010; Ramos-Gonzalez, 2014). In the national assessment of GI research by Wickham et al. (2010), for example, MSPA is highly advantageous because it explores the GI configuration and structural connectivity by extending the geographic scope and incorporating land-cover change information. As part of this information, GI mapping using MSPA can be applied to guide conservation and restoration decisions (e.g. loss of bridges signifies lost connectivity, which can potentially be used to prioritize restoration).

The integrated GIS methodology involves overlaying information. When combined with the principle of horizontal analysis of ecological processes, it has the potential to guide and inform the application of GI mapping at a range of scales and in diverse contexts (Table 1). As mentioned in key concerns b) above, six scales were identified in the reviewed literature: continental, international, national, sub-regional, urban and local scales. About 42% of the studies not only targeted but also conducted their GI mapping at the sub-regional scale, which includes sub-regions such as the area around Chesapeake Bay, U.S., and some others that might even cross national borders, e.g. Hungary and Austria, Germany and Czech Republic, Spain and Portugal. At sub-regional scale, these broad approaches usually identify land-cover types favorable to nature (e.g. green urban areas, agricultural systems with pastures and mosaics of parcels, forests and other semi-natural or natural dry lands, wetlands and water bodies) that provide a link between high-quality nature areas (Sundseth and Sylwester, 2009; EEA, 2011). About 33% of the studies were conducted at the urban scale. We observed an increase of GI mapping at the urban scale since 2014. This might result from the Urban Atlas which contains a high spatial resolution land-use database readily available in Europe for the points in time 2006 and 2012 (EEA, 2011). In this case, Larondelle et al. gave an extraordinary example for mapping the diversity of regulating ecosystem services in European cities (Larondelle et al., 2014). At the Pan-European scale, 6% of the articles dealt with the regulation of water flows and temperature control (Mubareka et al., 2013; Snäll et al., 2016; Liquete et al., 2015). Gill et al. (2008) suggest that more attempts should be made to link GI categories to the potential benefits and functions provided. In our review of all the literature, we found that there were only three publications (Barredo et al., 2016; Weber et al., 2006; Wickham et al., 2010) that give accuracy and precision of their mapping approaches, and more than two thirds of the articles did not address the question of rigor at all. Besides, when critically reviewing GI mapping tools, we illustrate a selection in Table 2, with respect to their contributions and limitations for GI planning.

In Table 3, the GI functional analysis is still lacking in 40% of all the reviewed literature (n = 67). About 60% of the articles analyzed looked at different GI functions, such as regulation of water flows (11.48%), temperature control (9.02%), accessibility for exercise and amenity (6.56%) and recreation (6.56%). GI functional analysis can also be described in terms of two main GI roles: 1) improving ecosystem functioning and promoting ecosystem services; 2) promoting societal wellbeing and health. The other two roles addressing the multifunctionality of GI are comparatively weak (EC, 2012), namely, 3) protecting ecosystems state and biodiversity, and 4) supporting the development of a green economy and sustainable land and water management. Further studies would be required to identify how multiple functions fit into these four roles of GI on the same piece of land. Going into future research, a comprehensive view of GI will be required which should focus on its multifunctionality at different scales.

4.2. Chinese approach towards GI implementation

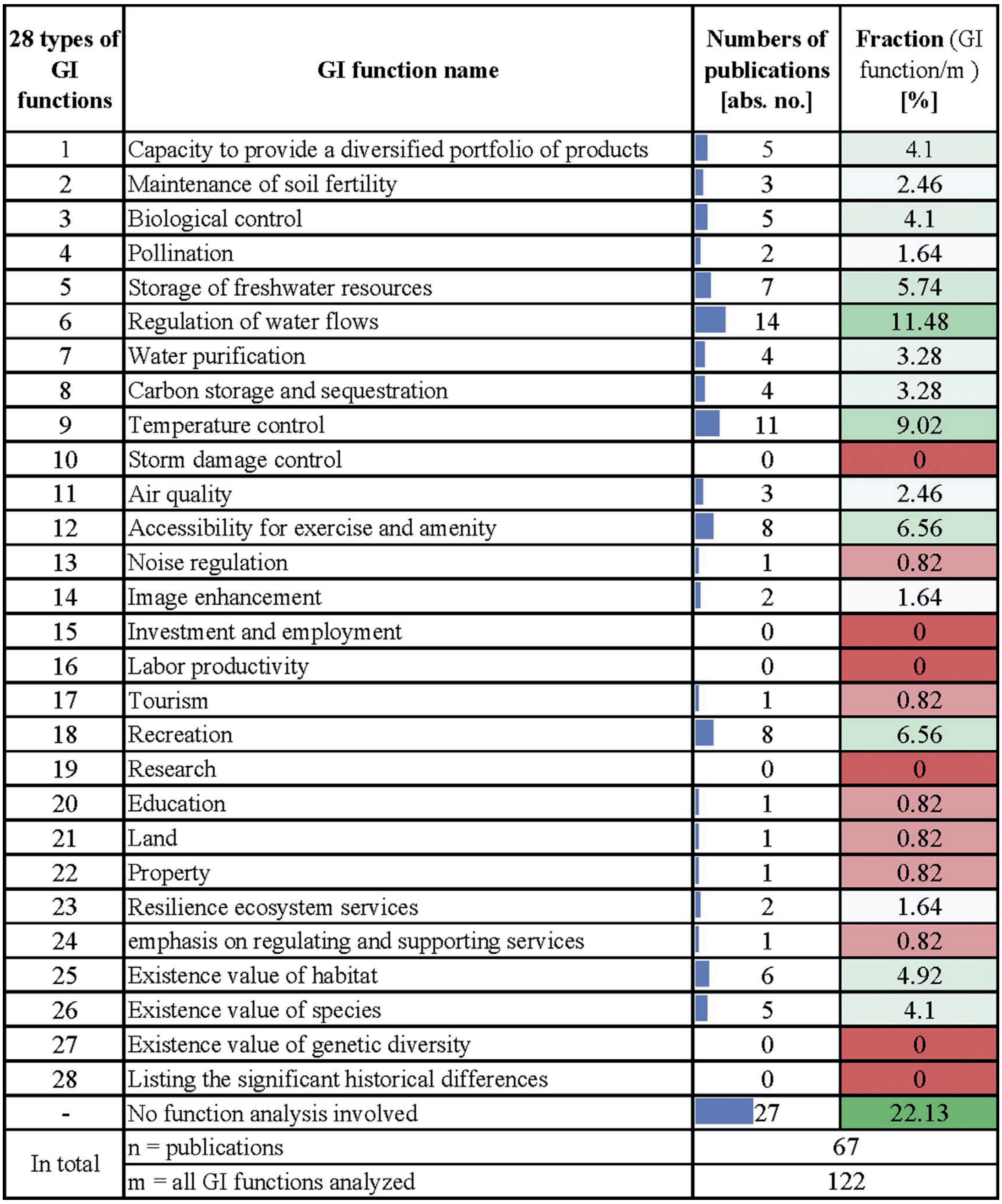
Beyond the referenced international literature published in English, a very large number of Chinese studies published in Mandarin have attracted little attention on the international level due to language conventions. We wish to remedy this situation by including all the Chinese-language articles containing GI research analysis in our review process. The relevant assessments provide valuable information about the key instruments of Chinese GI mapping approaches. The very first GI “seed” was sown in 1995 (Yu, 1995a), when Dr. Yu developed the concept of Security Patterns (SPs) (Yu, 1995a, 1995b, 1996). These SPs were the starting point of GI mapping in China. This key strategy of GI approaches was adopted by his planning team at Peking University and Turenscape, and was applied in the context of Chinese urbanization, e.g. Taizhou city in 2005 (Yu et al., 2005), growth planning for Beijing based on ecological infrastructure in 2011 (Yu et al., 2011), and urban river system of Liupanshui in 2014 (Yu and Turenscape, 2014; Yu, 2014a). Yu’s ideas comprise SPs actually conceived as GI to support abiotic, biotic and cultural functions (Ahern, 2007), thereby providing

Table 2
Critical review of selected GI mapping tools (adapted and cited from Lovell and Taylor (2013) and Tzoulas et al. (2007)).

Tools name	Methodology	Key purpose	Contributions to early stages of GI planning	Limitations
Life Cycle Assessment (LCA)	accounts for a broad range of categories such as water, energy use, greenhouse effect, toxicity, resource extraction, and land use based on international standards	evaluate or compare the environmental impacts of distinct green spaces (e.g. energy and material inputs and outputs;	Carbon Footprint analysis; Farm Carbon Assessment Tool; Climate Leadership in Parks	Generally, lacking in consideration of cultural values and social justice issues, although some attempts have been made to include these dimensions as one part of LCA in an effort to better align with sustainability goals.
Multifunctional Landscape Assessment Tool	The input data including the area of each habitat type, its functional attributes, and ratings of each attribute based on user perception and expert assessment depending on the site-specific context.	evaluate the design of agro-ecosystems	Help landowners and planners make informed decisions about land use that take into consideration the multifunctionality of the current system and the potential future functions	Limited in the ability to capture multiple spatial and temporal scales simultaneously, though the assessment could demonstrate differences in time and space dimensions.
Urban Forest Effects Model (UFORE)	The assessment of urban forest structure is conducted through aerial and ground-based measurements to determine area of tree cover, number of trees, species composition, tree biomass, and other relevant factors	assess forest structure and functions, and used to plan tree establishment to support desired functions	Help in calculating functions provided by local urban forests, such as air pollution removal, carbon sequestration, volatile organic compounds emissions, and energy conservation for nearby buildings.	Designed for woody plant cover, so it does not account for other types of vegetation and cover, and focuses heavily on ecological functions, mostly neglecting cultural and production functions

Table 3

GI functional analysis in GI mapping (column *Numbers of publications* illustrate the absolute number of publications that involve GI functional analysis for respective GI function; bars in column *Numbers of publications* illustrate the proportion of articles that include GI functional analysis in relation to n = 67; *Fraction* illustrates the respective fraction of the named GI function to all GI functions analyzed in the literature for m = 122). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article).



28 types of GI functions	GI function name	Numbers of publications [abs. no.]	Fraction (GI function/m) [%]
1	Capacity to provide a diversified portfolio of products	5	4.1
2	Maintenance of soil fertility	3	2.46
3	Biological control	5	4.1
4	Pollination	2	1.64
5	Storage of freshwater resources	7	5.74
6	Regulation of water flows	14	11.48
7	Water purification	4	3.28
8	Carbon storage and sequestration	4	3.28
9	Temperature control	11	9.02
10	Storm damage control	0	0
11	Air quality	3	2.46
12	Accessibility for exercise and amenity	8	6.56
13	Noise regulation	1	0.82
14	Image enhancement	2	1.64
15	Investment and employment	0	0
16	Labor productivity	0	0
17	Tourism	1	0.82
18	Recreation	8	6.56
19	Research	0	0
20	Education	1	0.82
21	Land	1	0.82
22	Property	1	0.82
23	Resilience ecosystem services	2	1.64
24	emphasis on regulating and supporting services	1	0.82
25	Existence value of habitat	6	4.92
26	Existence value of species	5	4.1
27	Existence value of genetic diversity	0	0
28	Listing the significant historical differences	0	0
-	No function analysis involved	27	22.13
In total	n = publications	67	
	m = all GI functions analyzed	122	

Online version: in column Fraction red means rare and green means a bigger share, the greener the more prevalent.
Print version: the columnar illustrates the amount of GI functional analysis involved.

sustainable ESS (Yu, 2011). As an application of this GI approach, the National Ecological Security Pattern Plan (2008) included each individual ecological process analysis and evaluation based on individual ecological SPs – headwater conservation, storm water management, flood control, remediation of desertification, soil erosion prevention and biodiversity conservation (Yu, 2014b). The GI approach carried out by Turenscape was first realized in Taizhou city (Fig. 3), where the "water town" planning concept (Ahern, 2007) integrates a man-made bifurcation to restore the ecological and social functions of rivers in this city. Before this concept was transferred into practice the rivers had been straightened and channelized during rapid urban sprawl processes (Fig. 3, from (a) to (d)). This initial Chinese project gave priority to river networks by focusing on flood hazard management and the river's ecological functions for neighborhoods.

Especially in the context of Chinese urbanization, extreme events could affect neighboring areas located in critical lower land, i.e. wetlands, near rivers and lakes. Over the last decades, concrete dams and banks have been built to protect such areas, without connecting urbanites to nature (Fig. 3 (a) and (c)). Yu recognized how important nature-related SPs are for adapted urban solutions. He therefore replaced previously man-made gray infrastructure with new GI elements (Fig. 3 (b) and (d)). Yu's core idea of SPs and their application are regarded as

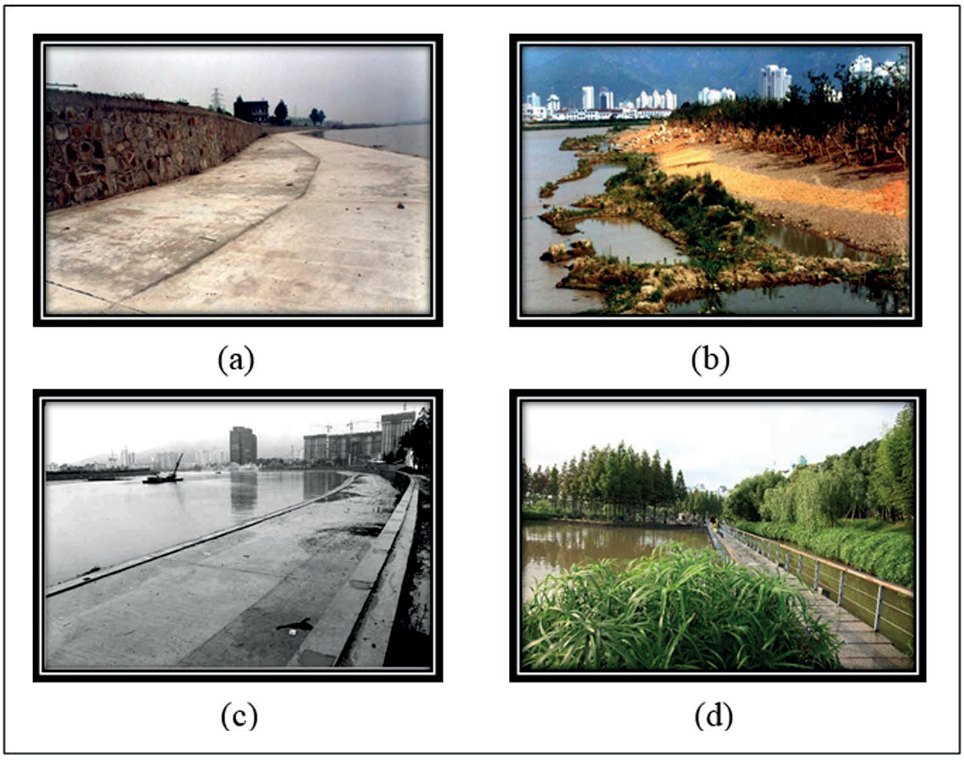
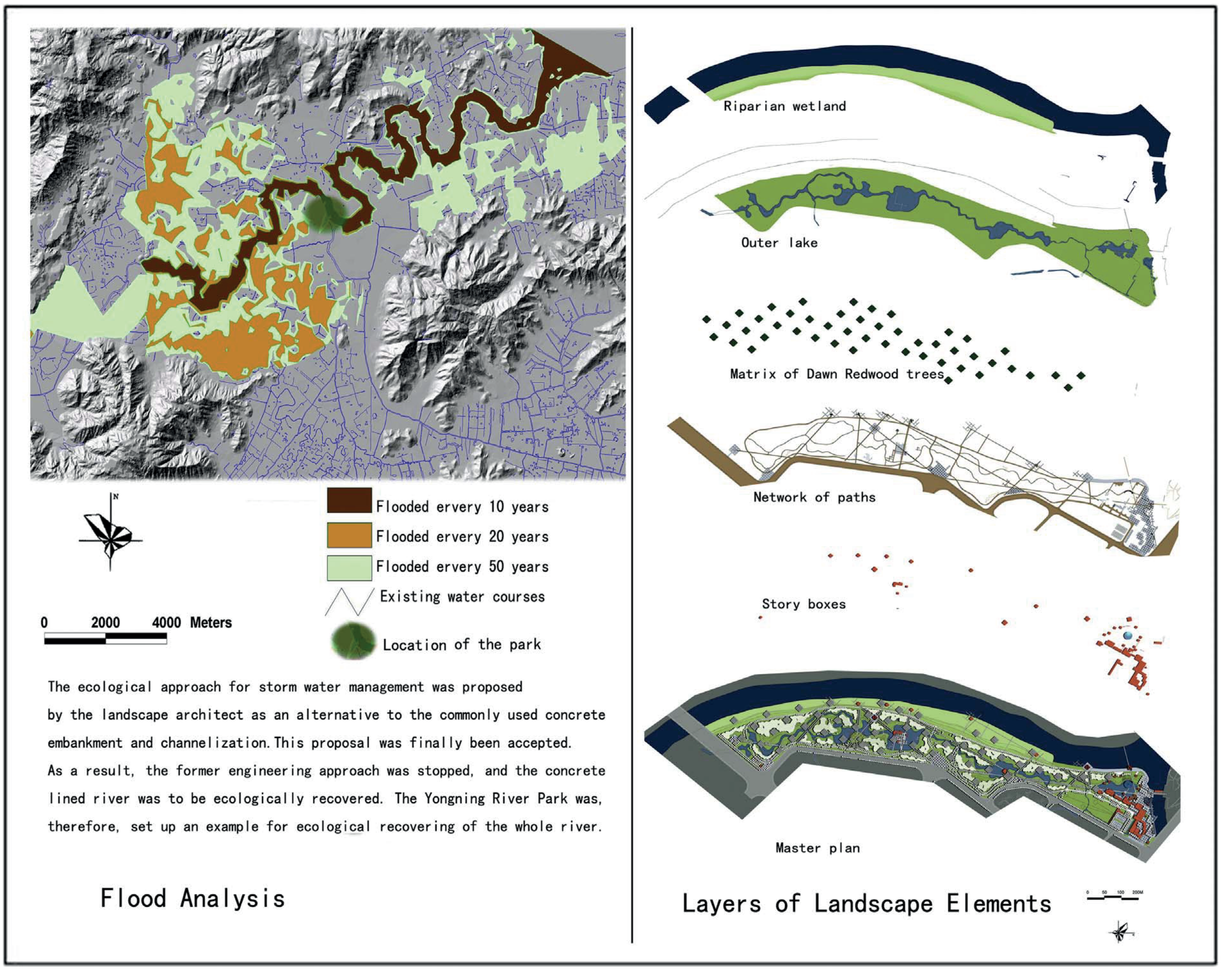


Fig. 3. The Chinese approach to GI implementation ((a) and (b) are the photos before and after GI design in the city of Taizhou, China; (c) and (d) show the public park beside the Yongning river before and after implementation of Taizhou's GI plan; photos with kind permission of Prof. Yu).



The ecological approach for storm water management was proposed by the landscape architect as an alternative to the commonly used concrete embankment and channelization. This proposal was finally been accepted. As a result, the former engineering approach was stopped, and the concrete lined river was to be ecologically recovered. The Yongning River Park was, therefore, set up an example for ecological recovering of the whole river.

Fig. 4. Flood prevention Security Patterns (SPs) at various security levels (Graphics with kind permission of Prof. Yu).

a milestone in the quest for more resilient cities in China that benefit from the GI concept. Hence, provision of ecosystem services and regulating functions for flood prevention have become accepted as useful instruments to secure accessibility at three probable flood-prone levels in China (hq 10, 20 and 50; i.e. hazard quotient for one event in 10, 20, 50 years) (Fig. 4). The concept of SPs also contributes to the GI mapping approach through the use of least-distance modeling tools to identify four structural components on the accessibility surfaces: buffer zones, inter-source linkages, radiating routes and strategic points (Yu, 1995b, 1996, 2014a; Dan, 2012).

5. Analysis and assessment

5.1. Concepts and key definitions related to GI

Our literature analysis shows that GI research has been conducted in several disciplines including urban ecology (Hostetler et al., 2011; Pinho et al., 2016; Qureshi et al., 2010), landscape ecology (Breuste et al., 2008; Chang et al., 2015; La Rosa and Privitera, 2013), sustainable development (Angelstam et al., 2013; Vollmer and Gret-Regamey, 2013), ecosystems and ecosystem services (Andersson et al., 2014; De Groot et al., 2010; Young, 2011; Lovell and Taylor, 2013; Young and McPherson, 2013; Zölch et al., 2016). All these ecological disciplines provide fundamentals for GI development (Young et al., 2014) and, to some extent, contribute to GI planning and implementation. However, their interdisciplinary concepts have customized foci so that research on the benefits, functions and key principles of GI cannot be conducted by making direct use of these findings. Using certain terminologies and definitions without an underlying conceptual hypothesis or specific differentiation may, in our opinion, serve to weaken the effectiveness of GI and its attraction as an innovation, let alone for its multifunctionality. Indeed, we have addressed the issue of conceptual ambiguity and the widespread citation of GI-related concepts in Table 4 at some conferences. One of these are the debates at the Royal Town Planning Institute Yorkshire Conference Series titled “Green Space, Green Belt and Green Infrastructure”, February, 24, 2010, in Leeds (Wright, 2011), presented that GI has tended to be a ‘corruptible concept’ that generates confusion (Collinge, 2010) because potential environmental damage might be justified by other environmental benefits since its ambiguity (Wright, 2011). It concerns us that ambiguity of GI can be easily co-opted by certain political agendas, thereby hindering its practical application. In the following, we seek to pay particular attention to certain kinds of cross-references that might intensify these risks when it comes to putting the GI concept into practice. The above-mentioned concepts and their key definitions are set out in Table 4.

Our findings show how important it is to distinguish when using GI: some citations use GI as reference to green areas, whereas other citations refer to GI concept to emphasize the underlying approach. For example, in some articles GI is equated with green areas without any further distinguishing description (Ramos-Gonzalez, 2014; Kati and Jari, 2016). Yet, the nature of its concept is not clarified in this context, thus leading the term GI in an ambiguous direction. Our intention is to analyze GI as a concept, rather than its use as well-recognized functions of so-called green areas, GI or urban vegetation. The latter only consider the vital role of GI strategies in relation to urban dwellers, and to their critical functions in mitigating urban heat island effects and building resilience against natural hazards (Ramos-Gonzalez, 2014; Demuzere et al., 2014). In contrast to this usage, we argue that the creative potential of GI must explicitly incorporate its multifunctionality and connectivity, because such haphazard or discretionary use may water down the GI concept and related strategies for land use policy.

The most recent viewpoint article on GI by Garmendia et al. (2016) supports our conclusions. They identify the concept of GI as a boundary object that establishes links among policy makers, developers and different academic disciplines. In this context, the authors pinpoint the risk of adopting GI as a biodiversity conservation concept without having a standard definition. We concur with Garmendia et al. (2016) stating that further research is needed to improve our understanding not only of the structural connectivity created by the physical characteristics of the landscape as GI but also of functional connectivity. Only with improved understanding can we hope to discover how genes, individuals, or populations are able to move through new landscapes (Garmendia et al., 2016). When GI is used as a flagship, usually represented by some of its elements such as green corridors (Van der Windt and Swart, 2008; Shwartz et al., 2014; Snäll et al., 2016; Panzacchi et al., 2016), urban gardens (Cameron et al., 2012; Hunter and Brown, 2012) as well as urban parks (Voigt et al., 2014), and green roofs (Carter and Fowler, 2008; Williams et al., 2014; Dagenais et al., 2016), it paints a confusing picture. This lack of clarity does not make the concept as valuable for biodiversity as it is often portrayed to be (Garmendia et al., 2016), even though GI is a convenient concept for policy makers (Cameron and Blanusa, 2016). In our opinion, this kind of discretionary use weakens GI as a concept because it fails to consider synergies and trade-offs arising from its multiple functions. This is highly counterproductive, as the latter signify the core idea of GI and represent its multifunctional attraction.

To give answers to our first research objective on the state of the art of GI, the comparison of overlapping categories helps identifying and clarifying conceptual relationships in multidisciplinary research. It is useful for planners, scientists and civil society to be realistic about the potentials and the limitations of GI when it comes to implementation. Our findings regarding GI-related categories and key definitions reveal a bottleneck in that the analyzed research focuses narrowly on their single functions and multifunctionality. These approaches need to be delineated further. In Table 4, they are marked in bold to express the need for further research. Given that in literature, GI functions and multifunctionality are listed without further definition, they usually capture a broad understanding of functions − ranging from soil development processes and support of species movement to physical recreation (e.g. Llausas and Roe, 2012; Ahern, 2007) etc., with no specification of their intrinsic characteristics. We argue that much greater clarity is required regarding the functions claimed for GI (Pataki et al., 2011) in order to to evaluate its efficacy.

In our view, it is important to understand possible interactional (for internal) and additional (for the whole system) effects in order to assess multifunctionality (EC, 2012). Furthermore, a workable conceptual framework for a sustainable GI requires that its functions and objectives are clearly identified so that GI can be assessed in terms of its own performance or effectiveness.

5.2. From functions to multifunctionality

The demand for sustainable land developments brought forward several concepts for Land Use Functions (LUFs). They might refer to different landscapes such as agricultural or urban. A strand of research was conducted to assess the impact of land use changes by specific land use functions to balance requirements and potentials of a landscape, exemplified for agriculture. This sequence of research also helps to understand the significance of multifunctional concepts as a balanced approach towards sustainability (Wiggering et al., 2003, 2006; Pérez-Soba et al., 2008; König et al., 2013).

GI draws attention especially to the issues addressed in landscape and urban planning (Benedict and McMahon, 2002) and landscape ecology (e.g. Jongman and Pungetti, 2004). But when it comes to ecology and biodiversity conservation, the concept of GI (especially with respect to urban planning and regeneration projects) is framed by the notions of habitat creation and restoration (Perrow and Davy, 2002; Weber et al., 2006; Eigenbrod et al., 2008; Lovell et al., 2010; Edwards et al., 2013; Patru-Stupariu et al., 2013; Eigenbrod et al., 2015), biodiversity (Poll et al., 2016; Herzog, 2016; Van Teeffelen et al., 2015), ecological networks (Fischer and Lindenmayer, 2007; Ignatieva et al.,

Table 4
GI-related concepts and key definitions.

Concepts related to GI development	Key definitions
Ecosystem services	Benefits humans derive from ecosystems which are produced by interrelations *within ecosystems*. They include supporting, provisioning, regulating, and cultural services that directly and indirectly affect people (MA, 2005; TEEB, 2010).
Landscape services	Benefits humans derive from *landscape*, expressed as a structure-function-value chain to inform *landscape development* (Termorshuizen and Opdam, 2009).
Ecosystem functions	The subset of the interactions between biophysical structures, *biodiversity* and ecosystem processes that underpin the capacity of an ecosystem to provide ecosystem services (TEEB, 2010). The capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly (De Groot, 1992; De Groot and Hein, 2007), including biotic, *bio-chemical and abiotic processes, within and between ecosystems* (Brussard et al., 1998; Lovett et al., 2005; Turner, 2005)
Landscape functions	The capacity of a landscape to provide goods and services to society. These goods and services are all benefits people obtain from *landscape*, such as *food, fresh water* and recreational benefits (Millennium Ecosystem Assessment, 2003).
Ecological functions	Those that provide services that moderate climatic extremes, *cycle nutrients, detoxify wastes, control pests, maintain biodiversity* and purify air and *water* among other services (ESA, 2006).
Land Use Functions (LUFs)	Defined as the private and public goods and services provided by multifunctional land uses *at regional scale*, that summarize the most relevant economic, environmental and societal aspects *with specifics for agricultural areas* (Pérez-Soba et al., 2008; based on Wiggering et al., 2003, 2006). As for the differences among ecosystem functions, ecosystem services, landscape functions and LUFs, our opinions are in accordance with Schößer et al. (2010, pp. 164–168).
Green infrastructure functions	So far they are grouped as ecological, social, and economic functions (Pauleit et al., 2011) or follow an alternative classification, such as the abiotic, biotic, and cultural functions of green spaces (Ahern 2007). This needs to be rendered much more specifically (see Section 5.2).
Green spaces	Well-structured vegetated pieces of land located in a city with differentiations in vegetation cover. They are one of the most important components of GI, and considered as public goods which allow free access to all citizens and represent pockets of nature for all residents. (Banzhaf et al., 2014; De la Barrera et al., 2016).
Landscape sustainability	*Capacity of the landscape* to consistently provide long-term, landscape-specific ecosystem services essential for maintaining and improving human well-being (Wu, 2013).
Multifunctional landscapes	*Landscapes* that provide a range of beneficial functions across production, ecological, and cultural dimensions, considering the needs and preferences of the owners and users (Lovell et al., 2010)
Green infrastructure multifunctionality	The ability to provide multiple or cross-cutting functions, by integrating different activities and land use, on individual sites and across a whole green infrastructure network (Natural England, 2009). The potential for green infrastructure to have a range of functions, to deliver a broad scope of ecosystem services (Natural England, 2009). This, too, needs to be rendered much more specifically (see Section 5.2).

(Left column: those concepts are in bold that need to be rendered more specifically; right column: major differences are highlighted in italics).

2011), and, increasingly, by ESS (Hoang and Fenner, 2016; Maes et al., 2015; Schindler et al., 2014; Snäll et al., 2016). Simultaneously, GI projects display considerable diversity in terms of scales, from the neighborhood scale e.g. depictions of green roofs (Williams et al., 2014; Peng and Jim, 2013), effect analysis on trees, green roofs and green façades (Zölch et al., 2016), through local and regional storm water management (Ahern, 2007), to large national ecological networks (Weber and Allen, 2010).

As the concept of ESS is fundamental to understand GI, it is applicable at a range of scales. Some authors present the benefits of GI in the light of ESS because the latter provide a relatively consistent and effective language that enjoys a growing resonance amongst policy makers and other stakeholders (e.g. Naumann et al., 2011a; Plieninger et al., 2013; Kukkala and Moilanen, 2016; Willcock et al., 2016). However, the connections between GI, ESS and natural capital have not been made explicit since the concept of GI first emerged. The functions associated with GI give the concept distinctiveness and added value compared to the more general and implicit descriptions of ESS. In our opinion, the specific and explicit functions of GI ought to encompass the spatial targets of ESS, hereafter GI implementation, their spatial connectivity and specific indicators for assessing the effects of GI implementation (EEA, 2011).

In academic research, ESS classifications are slowly being transferred over into GI analysis. Typical GI classification methods are underpinned by the widely accepted conceptual framework of ESS (EEA, 2011, 2014; Liquete et al., 2015; Maes et al., 2015; Norton et al., 2015; Kopperoinen et al., 2014). For instance, the Liverpool GI Strategy Action Plan (version 1.0) assessed six priorities being subdivided into 28 GI functions, ranging from those related to managing water, such as water interception and storage, to others referring to recreation, aesthetic and carbon sequestration functions (TMF, 2010). Its subsequently updated GI Framework Technical Document (version 1.2) points at the GI multifunctionality solution. It includes enhancing the ecological framework and developing the rural economy, but as a deficiency, it simply assesses *four* priorities (i.e. [in italics] *setting the scene for growth; supporting adaptation to climate change; providing recreation, leisure and tourism; supporting health and well-being* (TMF, 2013), even though substantial progress in multifunctionality analysis was made for each of these priorities from version 1.0–1.2. For a GI multifunctional assessment further study is still demanding: when it comes to pragmatic implementation, policymakers may wish to consider weighting their policies towards the protection of GI functionality in urban areas. A weakness is that no underlying version introduces weighting or relates GI functions to the demand for GI benefits from a social perspective. The latter is, however, regarded as a crucial part when assessing multifunctional GI (Hansen and Pauleit, 2014).

Another classification method divides GI functions into ten benefit groups, which again include 28 different functions (European Commission, 2013). This method has been employed to case studies in the Regional Plan of Territorial Planning in Metropolitan Area of Lisbon, Portugal, the Network of Ecological Corridors in the Autonomous Community of Madrid, Spain, and the Green Roofs initiatives in Basel, Switzerland (Davis, 2010). But in their in-depth case analyses of urban GI, the Lisbon case involves four benefit groups at regional scale, i.e. ecosystem resilience, climate change adaptation, disaster prevention and ecosystem service provision. As for Ecological Corridors in Madrid and Basel's Green Roof Initiative, their impact analyses concern merely two GI benefit groups, i.e. climate change adaptation and ecosystem services provision. One deficiency is turned out, for instance, in Basel's Green Roof Initiative, where only three main indicators (proportion of green surface area close to urban areas, degree of usage by target species with controls and their population trends, and area of land management to High Nature Value (HNV) standard) are calculated based on its two aspects of GI benefit groups. Another shortcoming is also reflected, for example, in the planning document for the Network of Ecological Corridors in the Autonomous Community of Madrid. Its implementation carried out at local administration has been weakened in lack of inter-administrative agreements, even though it involves two facets of GI benefits during its designing and approving stage at regional administration.

In a nutshell, all these three case analyses result in inevitable difficulties in GI assessment, because GI assessment depends on an integrative indicator framework on GI multiple functions extracted from benefit groups. Even though it is worthwhile mentioning that these plans justify a high potential of GI concept to deliver multiple benefits to society, they do not have enough consideration about such multiple functions to contribute to GI assessment. Consequently, they fail to draw lessons for GI strategy, let alone for its network and multifunctionality. Multifunctionality must be considered as one stage in the decision-making process in which we necessarily make choices among functions.

In recent years, multifunctional GI has been recognized as a condition for sustainability (Brandt and Vejre, 2004; Breuste et al., 2015; Zander et al., 2007) and has also been extended to include intensively-managed ecosystems (Lovell and Johnston, 2009; Harrison et al., 2010). We could observe that a growing number of researchers are emphasizing the importance of multifunctionality as a fundamental property of sustainable development (Selman, 2009; EC, 2012; Maes et al., 2013; Madureira and Andresen, 2014). They all have reiterated the multifunctionality of GI as being one of its greatest strengths (Davies et al., 2006, p. 42; Kimmel et al., 2013, p. 10; Civic, 2014). The core ideas of GI, especially its multifunctionality, are comparatively more specific than those of more abstract concepts such as the complementary "sustainable development". Hansen and Pauleit (2014) provided a comprehensive perspective to value multifunctionality by taking the following aspects into consideration: GI integrity, hotspots, synergies and trade-offs, supply and demand of services and stakeholder preferences (Hansen et al., 2014). In cities, GI consists of planning and designing a multifunctional network of interconnected patches of vegetation cover and permeable soils in order to restructure the landscape mosaic at various scales. For instance, trees along streets and riparian corridors could connect parks and other green areas. The aim is to conserve or re-establish key social-ecological functions and services, with a variety of abiotic, biotic, and cultural benefits (Benedict and McMahon, 2006; Ahern, 2007). This beneficial esteem comes from "direct experience with nature [through which] people come to understand its value and gain better appreciation of the importance of healthy habitats and ecosystems" (Newman and Jennings, 2008, p. 64). According to 28 papers specifically on GI multifunctionality the priorities of GI multifunctionality are geared towards biodiversity, floodplain management, local temperature regulation (Norton et al., 2015) and provision of public green spaces (Madureira and Andresen, 2014; Connop et al., 2016; Herzog, 2016; Tiwary et al., 2016).

Towards a better understanding of GI from functions to multifunctionality, multifunctionality should rather be augmented by two dimensions: 1) the functions of GI at multiple scales and their respective roles, and 2) the different functions of GI properties performed simultaneously in addition to their obvious primary functions. Rather than serving just one purpose, such as a green roof top, GI can provide thermo-regulation, water retention, habitat for wildlife, and space for recreation. One key objective of GI planning should be to perform as many functions as possible in a given setting. In our view, restricted or single functionality is appropriate only where there is an overriding function that must be safeguarded because of legislation or strategic significance. Street trees, for example, add aesthetic quality to an urban area but also reduce airborne pollution, mitigate wind turbulence, provide shade and can even increase biodiversity. At this point, these functions can be explained by their long-term, structural and connective character for the whole ESS. Therefore the two dimensions of GI multifunctionality should be addressed when selecting their respective indicators for GI assessment. In addition, a robust multidisciplinary approach involving multiple aspects of GI functions should address not only the individual benefits of each function but also their spatial interactions.

Of the six papers in the ISI Web of Science specifically dealing with multifunctional GI assessment, just a single one emphasizes the importance of the multifunctionality of urban GI. However, even this one puts forward simply two indicators (i.e. the local temperature regulation and population proximity to public green spaces), even though it eventually provides the crucial conclusion that a shift from generic assumptions to local assessment may help understand and analyze GI evolution (Madureira and Andresen, 2014). Although this study gives a localized sample in multifunctional GI analysis, it obviously fails to make a more synthetic assessment, since some other crucial functions of GI (such as recreation or sense of place or enhanced biodiversity) are not considered. Urban GI is multifunctional in that it addresses geologic, hydrologic, biotic, circulatory, social, and metabolic systems (Herzog, 2016), besides stimulating economic development.

6. Discussion and conclusions

In this review, we explore the conceptual evolution defining GI and, for a better understanding, we address the multifunctionality of GI. Our findings show how important it is to comprehend GI in a differentiated way for purposes of spatial planning. When we do so, we elicit a wider range of functions in relation to environment, society, and economy. To deepen our knowledge of GI concept, we investigated existing GI mapping approaches and tools at various spatial scales. Having found gaps between GI mapping and GI functional analysis, we conclude that these gaps make it difficult to monitor the impacts of GI and to evaluate it at the appropriate level of scientific rigor.

In order to steer and reinforce GI concept in a more efficient direction, we put forward a set of six principles that should be addressed in the future, drawing from the widely cited main GI principles put forward by Pauleit et al. (2011), Ely and Pitman (2014), Mell (2014) and Davies et al. (2015). Our proposed principles are sustainability, multifunctionality, connectivity, biodiversity targets, urban focus, and collaboration. To achieve sustainability at various scales, GI must be conceived of as a genuinely workable means to improve and contribute to multifunctionality. To think merely in terms of damage control − in other words, avoiding or minimizing impacts related to infrastructure development − is far too limited and will greatly diminish the potential of GI innovation. With reference to biodiversity targets, the GI approach is regarded as a win–win method that is guided by landscape considerations which, when implemented, can enhance biodiversity and generate broader ecological benefits. It is obvious that these GI principles need to be applied to the urban area first and foremost, because in this densely populated urban landscape the demand is pressing with multiple gains for ecological, social and human health. Our results emphasize that multifunctionality, as the latest conceptual evolution of GI, is the optimum approach to drive many aspects and functions of GI, in order to achieve success in urban spatial planning.

With regard to human wellbeing in cities, we are in the same line as Hansen and Pauleit (2014) stating that sustainable urban development can be achieved by further comprehensive assessment of GI multifunctionality. Their exploration (Hansen et al., 2016) provided a thorough perspective to value multifunctionality. Multifunctional GI, which would be closely related to and even decided by its features, plays an important role both in adapting to new urban environmental challenges and in mitigating urban environmental problems, increasing resilience, and maintaining quality of life.

We are convinced about the need to study the four roles of GI analyzed in Section 4.1 on the very same piece of land in order to measure its multiple functions. As a minimum quantity one performance or state indicator per GI function must be applied. To increase the efficacy of GI concept we recommend the analysis at several scales. Only by doing so the GI core concept can help deepen the practical understanding of its underlying multifunctionality, and simultaneously it will serve for comprehensive GI assessment. Hence, it might make GI concept “fit for purpose” so that its conceptual evolution and current developments match with its planning and implementation.

Owing to the different elements involved in GI, a multifunctional GI assessment should include the qualities of these elements, e.g. biodiversity conservation and cooling effects from green roofs, recreational availability, heat control by urban gardens, and mixed species richness in flora and fauna attributed to vegetated façades. To fill the detected gaps the assessment should consider the qualities of conservation and management as well, e.g. the social recognition that within our ecosystems humans are part of GI functions. Multifunctionality ought to be esteemed as one stage in the decision-making process in which we necessarily make choices among functions. It should not be seen as a direct and simple result of GI implementation. Notable achievements for the human habitat are gained when combining the conceptual framework of multifunctionality in GI planning for urban areas with the current knowledge on GI and ESS. To conclude, we want to emphasize that enhancing multifunctionality of GI in cities by linking ecological and social processes will maintain or even improve human wellbeing and thus foster a sustainable urban development.

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Appendix A. Supplementary data

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Paper II

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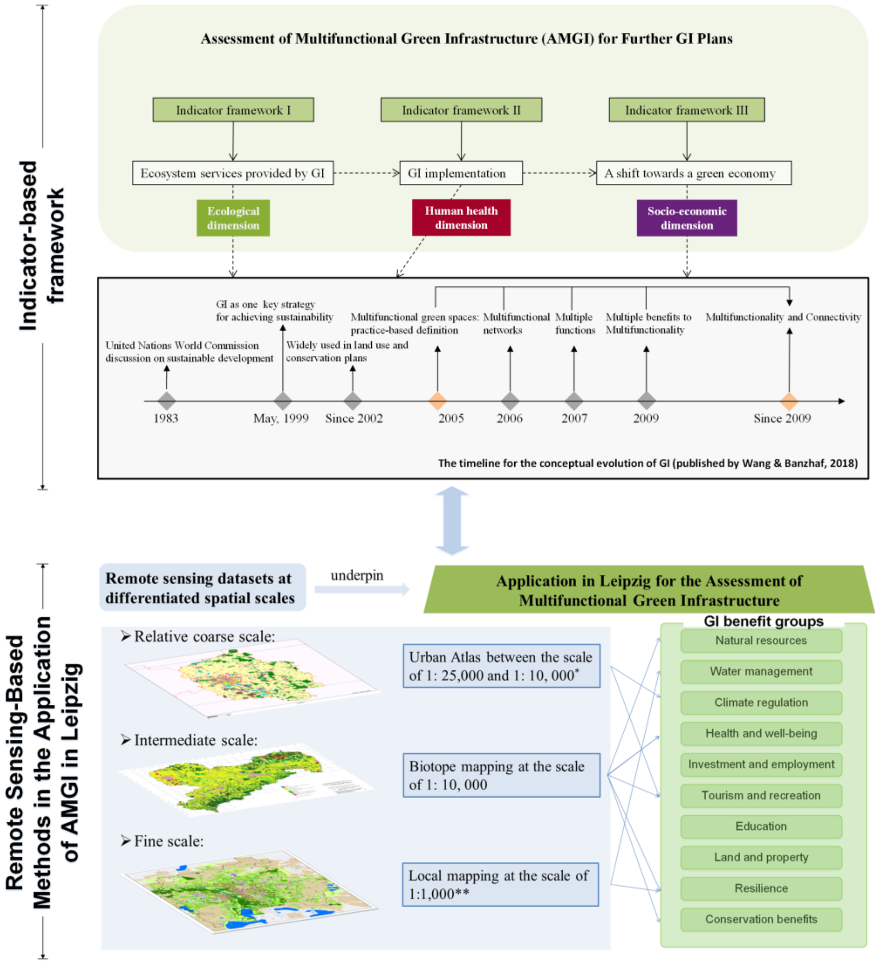

remote sensing

Article

An Integrated Indicator Framework for the Assessment of Multifunctional Green Infrastructure—Exemplified in a European City

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Abstract: The aim of this study is to provide an integrated indicator framework for the Assessment of Multifunctional Green Infrastructure (AMGI) to advance the evolution of the Green Infrastructure (GI) concept, and simultaneously deliver an approach do conduct a GI assessment using remote sensing datasets at multiple spatial and spectral scales. Based on this framework, we propose an explicit methodology for AMGI, while addressing the multi-dimensional pillars (ecology, socio-economy, socio-culture, and human health) for urban sustainability and the multifunctionality of GI. For the purpose of validation, we present the extensive process of employing our framework and methodology, and give an illustrative case exemplified in a European city, i.e., Leipzig, Germany. In this exemplification, we deployed three stages regarding how a single assessment can be conducted: from conceptual framework for priority setting, contextual assessment, to retrospective assessment. In this illustrative case study, we enclosed 18 indicators, as well as identified hot and cold spots of selected GI functions and their multifunctionality. A clear framework and methodology is crucial for the sustainable management of spatially oriented GI plans over time and for different stakeholder groups. Therefore, GI planners and policy makers may now refer to our integrative indicator framework and provided application methodology as common grounds for a better mutual understanding amongst scientists and stakeholders. This study contributes to discourses regarding the enhancement of the GI concept and is expected to provoke more discussion on the improvements of high-quality Remote Sensing (RS) data as well as the development of remote sensing-based methods at multiple spatial, temporal, and spectral scales to support GI plans.

Keywords: Ecosystem Services (ESS); multifunctionality; GI assessment; urban planning; sustainable development; remote sensing application

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1. Introduction

Green Infrastructure (GI) has been identified as one of several key strategies for promoting urban sustainability [1–4]. Urban GI has evolved since its inception in the 1990s [5], and it has been defined and interpreted in different ways, such as representing ecological networks of natural and semi-natural areas, approaches for sustainable storm-water management in urban areas, or the strategic planning of networks of green and blue spaces that meet multiple environmental, social, and economic objectives in urban environments at various scales [1,3]. As strategic planning, GI is a whole landscape approach in which all urban green and blue spaces, and even technical green vegetation systems, such as green roofs and walls, have the potential to contribute to the urban GI, regardless of origin and ownership [6,7]. Recent research in Europe has contributed to further advancements in the theoretical foundations of urban GI and assesses the state-of-the-art of its planning in practice [6,8]. It turns out that multifunctional GI has been recognized as strong support for sustainability [4,9], which has enormous potential to disclose the greatest number of benefits such as the protection of natural resources, water management, climate regulation, and the promotion of human health and well-being. Therefore, urban multifunctional GI can be a valuable tool to strategically promote sustainable development by addressing various dimensions of sustainability [10–12], provided that sustainability can be strengthened via a multi-dimensional analysis on ecology, the social economy, social culture, and human health [13]. However, since GI has been recognized as a concept and strategic planning is relatively new—in the realm of the last 20 years—studies concerning a thorough assessment of urban multifunctional GI are rather rare [1,3], both in long-term and at multiple spatial scales.

Frameworks and methodologies have recently emerged that aim to assess multifunctional GI through indicators (e.g., [14–18]), given that a systematic combination of several indicators is the best way to represent the overall performance and functions of GI [3,19]. In this context, it has been recognized that a better understanding of multifunctional GI is crucial for urban sustainable development [20,21]. Indeed, there is a growing number of frameworks (e.g., [2,17,19,22–26]) and most studies have provided useful insights into GI assessment. For example, the Common International Classification of Ecosystem Services (CICES) supplies a set of indicators on the basis of a cascade structure (i.e., provision, regulation, and cultural services [27]) to support Ecosystem Services (ESS) assessment [17,28]. Furthermore, The Economics of Ecosystem Services and Biodiversity (TEEB) [28] have informed the true economic value of ESSs, developed from the Millennium Ecosystem Assessment (MEA) [29]. As an advancement, the indicator frameworks from the Total Economic Value model by Vandermeulen, et al. [30] and GI valuation toolkit by East Midlands Development Agency (EMDA) in 2008 have recognized a range of GI values. They include direct use values (e.g., the supply of food and water) and the indirect use values (e.g., air and temperature regulation and non-use values like the protection for future generations [31]).

However, these frameworks are mainly restricted to a fractional GI assessment, such as cultural services provided by GI or to a limited number of GI functions [4]. Less is known regarding their spatial extents and their coverage of qualitative assessment or quantitative measures. It is thus hardly possible to obtain a full picture of multifunctional GI and to undertake a multifunctional GI assessment from only one of them. Moreover, the roles of urban multifunctional GI for promoting ESS [1] and societal health and wellbeing [3], supporting the development of a green economy [6,21,32], as well as sustainable land and water management ought to be reflected in the indicator framework to guide GI planning, management, and policy-making. The challenge remains, as there is a lack of an integrated indicator framework with which scientists and practitioners can undertake an individual assessment of multifunctional green infrastructure (AMGI), particularly concerning primary aspects of urban GI such as ESS provided by GI [22], multiple benefits and functions of GI [3], and the potential monetary value of GI functions [33,34]. As such, AMGI requires a combination of qualitative or quantitative assessments with quantitative measures, using input from both ecological and social sciences [1,3]. In the absence of an integrated indicator framework for multifunctional GI as well as the methodology to conduct AMGI, the AMGI is inclined to be selectively conducted [35,36] and thus leads to a slow uptake of GI in practice [36,37]. Furthermore, it results in the bias that GI, as strategic planning, may address either few functions or limited dimensions of sustainability. It is crucial, therefore, to know the central indicator frameworks for GI assessment that could convey the aforementioned major aspects of the urban GI concept, while providing a methodology to undertake AMGI using an indicator framework, because such an indicator framework can only be valid and further circulated if it can be applied to various cases. We hence amalgamate central indicator frameworks and come up with our research question: How can a single AMGI be conducted using an indicator framework?

In this paper, we first analyze prominent indicator frameworks for AMGI to establish an integrated indicator framework that allows for the reflection of significant aspects of the urban GI concept: the ESS provided by GI, multiple benefits and functions of GI, as well as GI valuations towards a green economy.

Based on this indicator framework, we develop an approach to undertake such an AMGI. Our aim is to introduce a new framework for GI assessment by enclosing multi-dimensional considerations for urban sustainable development. For the purpose of the illustration of our approach for urban GI assessment, we deploy the methodology in one European city, the City of Leipzig, Germany, and present the respective assessment results with all strengths and weaknesses. A cohesive, well-described assessment on multifunctional GI may stimulate further progress in developing GI strategies and adaptive evaluation methods to inform GI planning and implementation.

2. Materials

Our materials and datasets not only comprise indicator frameworks but also remote sensing data and products that bolster the potential and applications of our framework. For this reason, the underlying materials and data are twofold: one being the indicator frameworks and the other the exemplification in an urban area.

2.1. Selected Indicator Frameworks for AMGI

For the purpose of our methodology development, we selected three prominent frameworks that reflect the evolution of the GI concept (see Figure 1), while acknowledging that a great number of research has dealt with individual or groups of indicators to assess ESS (e.g., [12,38,39]). We shed light on the most noteworthy frameworks that encompass the primary aspects of GI and that were designed and applied for GI development. The selected three indicator-based frameworks (Figure 1) are:

- Indicator framework I for ESS assessment from MAES:

The indicator-based framework proposed for the Mapping and Assessment of Ecosystems and their Services in urban areas—Urban Ecosystems Forth Report (MAES, 2016, pp. 75–81) [22]. It is adapted and extracted from the Common International Classification of Ecosystem Services (CICES) with a more urban-focused purpose, namely urban GI and urban ecosystems [22].

- Indicator framework II for GI implementation from IEEP:

The indicator framework by the Institute for European Environmental Policy (IEEP) was selected since it is designed to assess various functions [2] provided by different GI types such as hedgerow, lawn/meadow, agroforestry, etc. We hereby refer to it as indicator framework II. It addresses the environmental, social, and economic benefits provided across differentiated GI types. Moreover, indicator framework II is supposed to support the assessment of urban GI that could be part of the GI strategy [40].

- Indicator framework III for supporting a shift towards a green economy from EMDA:

Supporting the transition towards a Green Economy is a major task for practitioners when putting frameworks into practice. The rationale for every GI investment requires a strict examination due to economic austerity [21,32,33]. The indicator framework III underscores the economic valuations of GI. We hence include indicator framework III, as it emphasizes the economic dimension of GI. It was first established in 2008 by the East Midlands Development Agency [25,41] and expanded the benefits of GI by initiating the awareness of its economic values [33,42]. It is then appreciated in the study of Green Infrastructure Implementation and Efficiency [2] to support the development of Green Infrastructure Strategy in cities. The EMDA addresses the economic valuation of GI as quantitative benefits to include the monetary aspect into GI assessment [26].

Given that indicator framework I emphasizes the ESS provided by urban GI; indicator framework II provides multiple GI benefit groups and incorporates human health aspects; indicator framework III adds to these frameworks by its focus on indicators for the economic valuation of GI benefits, they are selected as prominent frameworks for AMGI.

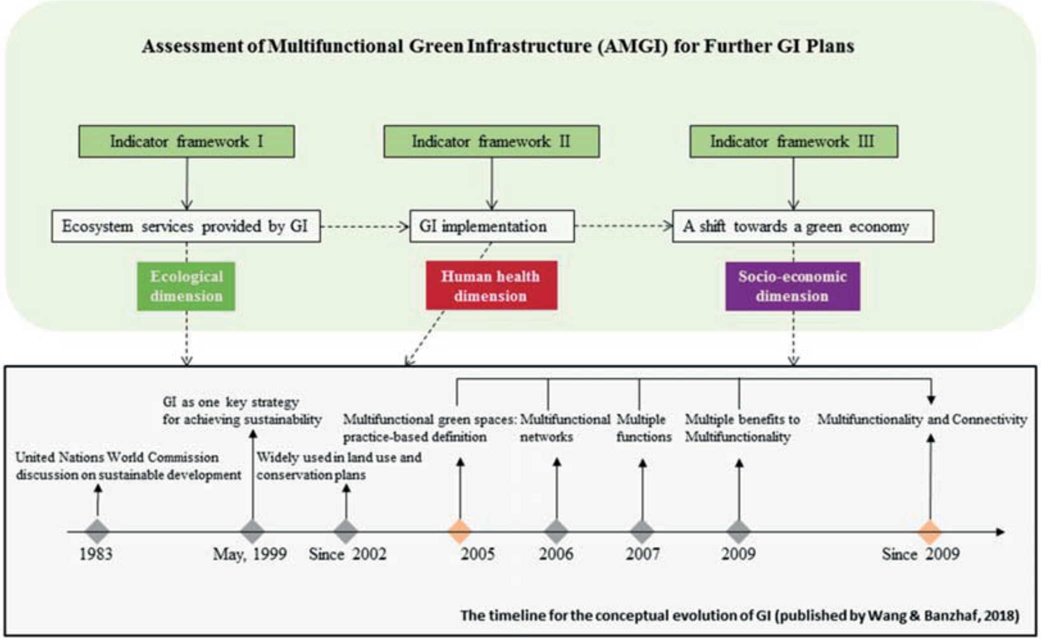

Figure 1. Potential contributions of selected indicator frameworks I to III for Assessment of Multifunctional Green Infrastructure (AMGI) (dashed arrows indicate the potential contributions; arrows show proven developments).

2.2. Remote Sensing Techniques as Essential Pillars for AMGI

At multiple scales, remote sensing plays a significant role for spatial analysis and thus also for our comprehensible methodology (Section 2.3) to undertake an AMGI. Since one single layer of earth observation data seldom provides the overall information on urban GI [4,43], analyzing the urban area at multiple scales by exploiting various Remote Sensing (RS) data is an excellent opportunity for the multifunctional GI assessment since these functions need to be understood at respective scales. Earth observation provides overall information on urban GI through the synergetic usage of different sensors [4,43]. Furthermore, indicators enclosed in the indicator framework are mostly based on remote sensing techniques. In order to extend applications of our indicator framework, we shed light on the significance of using multi-scale RS data.

In Europe, RS products for AMGI can be obtained at different scales: (i) at regional scale: the vector-based dataset Corine Land Cover (CLC) for 1990, 2000, 2006, 2012, and 2018 as well as the High Resolution Layers (HRL) which enclose categories such as forests, grasslands, imperviousness zones, permanent water bodies, and wetlands (raster-based as complementary to CORINE (Coordination of Information on the Environment) Land Cover datasets). Both of them cover Europe entirely, showing great advantages through regular updates (every six to 10 years); (ii) at the national level: e.g., Natura 2000 (N2K) for 2006 and 2012 across 28 EU nations; (iii) at the state or municipal level: e.g., Urban Atlas (UA) datasets and biotope mapping (based on aerial photography and ground investigations of individual habitats). For biotope mapping, internationally, there is a rising number of biotope mappings in countries such as South Korea [44], Turkey [45], China [46], and Norway [47]. For a country like Germany, where the biotope mapping has had a long-standing tradition of more than 45 years, RS orbital and aerial images are of great value, because they support the classification system of biotope types at one point in time over a large space. Thus, diversified sites and biotopes in urban areas are mapped and undergo long-term monitoring [48]. In Germany, biotope mapping is widely used for policy making with its long tradition in landscape planning and management [49]. For this reason, different satellite and aerial sensor systems may serve to enhance the potential applications of our indicator framework and methodology for AMGI. Multispectral orbital sensor systems like

Landsat, Sentinel, Spot, Rapid Eye (30 m, 20 m 6.5 m ground resolution, respectively), and aerial camera systems (40–20 cm ground resolution) that take digital color-infrared orthophotos provide significant support for AMGI. Both their regular uptakes and the choices they offer for image analyses, with their various spatial resolutions to investigate urban structural compositions and undertake mapping and monitoring procedures, are important inputs. The AMGI can select the respective RS datasets with their exquisite spectral information from visible to near and shortwave infrared to identify GI types according to their spectral traits in urban areas. Thereby, more interrelations among different GI functions can be incorporated [4]. That is to say, these earth observation datasets are spatially explicit prerequisites for deriving indicators of multiple GI functions and thereby contributing to the AMGI. AMGI will benefit from multiple spatial scales and spectral information for which we only give limited insight into RS datasets in this paper. More research in the field of RS is being performed to merge very high resolution imageries with digital elevation and surface models for three-dimensional (3D) urban mapping [50] and GI assessment [3].

2.3. Earth Observation Datasets for the Exemplification in Leipzig, Germany

Three earth observation datasets have been used in our illustrative case of Leipzig:

(1) The land-cover data originated from the European Urban Atlas land cover dataset—Copernicus Land Monitoring Service [50]. It was obtained from the European Environment Agency (EEA, http://www.eea.europa.eu/data-and-maps/data/urban-atlas). For the first time slot, Urban Atlas data (2006) [1] conveys 305 larger urban zones (including commuting zones around cities) in the 27 countries of the EU for all the European core cities and respective larger urban zones with more than 100,000 inhabitants. Its products are combined image classifications with 20 m (shot-wave-infrared (SWIR) mode) to 10 m (near-infrared (NIR) and visible spectral) multispectral analysis for urban GI, being pan-sharpened to 5 m to 2.5 m spatial resolutions. The more recent slot, i.e., UA data for 2012, covers all European cities with a minimum of 50,000 inhabitants. Our application in Leipzig used the Urban Atlas data from 2012 [50].

(2) The Leipzig biotope mapping (2005) [51] extracted from the biotope map of Saxony. It is similarly structured to the Urban Atlas, as it includes both human-built classes as well as natural and semi-natural classes [51]. However, the data set is derived from 1:10,000 color-infrared orthophotos by the manual classification of biotopes with a minimal area of 0.25 ha [51]. This thematic information was produced by the "Sächsisches Landesamt für Umwelt Landwirtschaft und Geologie" (2008) [51]. Its classification system of biotope types gives abundant information on diversified sites and biotopes in urban areas [48]. Biotope mapping characterizes cities, especially urban areas, as a complex habitat mosaic [52], which are made up of various sub-units and forms. They are major components of our evaluating objects. This premise permits that its classification of urban spatial categories and matrix-patches mapping [53] may extensively facilitate the identification of several GI features such as deciduous forests and zoological gardens; whereas other datasets like Corine Land Cover cannot provide sufficient information on urban GI, due to their coarse spatial resolution or relatively rough taxonomy.

(3) The local Land Use and Land Cover (LULC) structural analysis for Leipzig in the year of 2012 [54,55]. To gain the spatial information on urban LULC at a very high resolution, we employed four-band color infrared digital orthophotos (DOP), a digital elevation model (DEM), and a digital surface model (DSM). These datasets were processed by an Object-based Image Analysis (OBIA) approach. The complex methodology of this OBIA mapping process is depicted by Banzhaf et al. [43,54], in which the different datasets were all rescaled to 1 m ground resolution for the year 2012. As for the demographic data, we employed the population data for 2012 collected by the city council [56], which includes all urban residents with their first and second place of residency in Leipzig. By including those with a second residency, we also pay tribute to international students, commuters, etc., which best generates a picture of the real users. The

respective usages of the three aforementioned earth observation datasets can be also found in following Table 2 (see Section 3.3).

3. Methods

The methodology section comprises the analysis of indicator frameworks and the other for the integrated framework application in Leipzig.

3.1. Analysis Method for Selected Indicator Frameworks

In the following, each indicator from these indicators frameworks is scrutinized with regards to (1) relevant spatial extent, (2) involved GI types (service provision units), (3) data availability, (4) their information regarding GI assessment (e.g., data sources and references/proven methods), and (5) whether it is a supply indicator or a demand indicator, by means of reviewing each indicator from its source listed in the respective framework (from the MAES, IEEP and EMDA) as well as other potentially updated studies in the Web of Science, Scopus, and Google Scholar databases.

Since indicator framework I only follows the structure provision, regulation and maintenance, and cultural ecosystem services, we have to classify all indicators into those ten GI benefit groups to allow for further comparison with the other two frameworks in the following sections. For classification reasons, we use the definitions of each GI benefit from indicator framework II and III. The corresponding relationships between ESS (provisioning, regulation and cultural services) and GI benefit groups are listed in Table 1 (code numbers refer to the respective indicators in Table A1).

Whenever the specific purpose of one of these 40 indicators was not clear or related to more than one dimension, we traced it back to its source and compared it carefully with the definition of relevant ecosystem services in CICES V5.1 [57] (the latest version released on January 2018) and the second [18] and forth [22] reports of MAES: Indicators for Ecosystem Assessments under Action 5 of the EU Biodiversity Strategy to 2020 and Urban Ecosystems. Apart from tracing back the framework as such, we also reviewed each indicator one by one concerning their reference sources to understand with which dimensions the respective indicator has addressed sustainability.

The structure transformation of indicator framework I facilitates its further comparison with the other two frameworks, since both indicator framework II and indicator framework III have already been sorted out as 10 GI benefit groups by Mazza et al. [2].

Table 1. Transformation of the structure of Indicator Framework I from Mapping and Assessment Ecosystem Services (MAES) into ten GI benefit groups (Indicator codes refer to Table A1).

MAES Classes	GI Benefit Groups	Indicator Codes from Indicator Framework I
Provision	Natural resources	01, 02, 05, 28, 29
	Water management	03, 04, 06
Regulation and maintenance	Climate regulation	07, 08, 10 to 16, 18, 20, 21
	Health and well-being *	09, 17, 19, 26
	Resilience	22, 23, 24, 25, 27
Cultural	Tourism and recreation	30 to 38
	Education	39
	Conservation benefits	40

(* GI benefit health and well-being relates to the indicators merely on human exposure, in alignment with the definition from the final report on GI implementation and Efficiency by Mazza et al. [2], although we are aware that health and well-being has a close connotation to cultural services. With regard to the definitions for GI benefits, we are in line with the source of indicator frameworks [2].)

3.2. Methodology Application of the Indicator Framework for AMGI

Conducting an AMGI at multiple spatial scales is important to fully capture the benefits of GI and to understand the interlinkages between GI at these scales. Our selected frameworks I to III were organized by 10 GI benefit groups in Figure 2, through which we may develop our methodology to AMGI. These 10 benefit groups are defined in the GI by Mazza et al. [2].

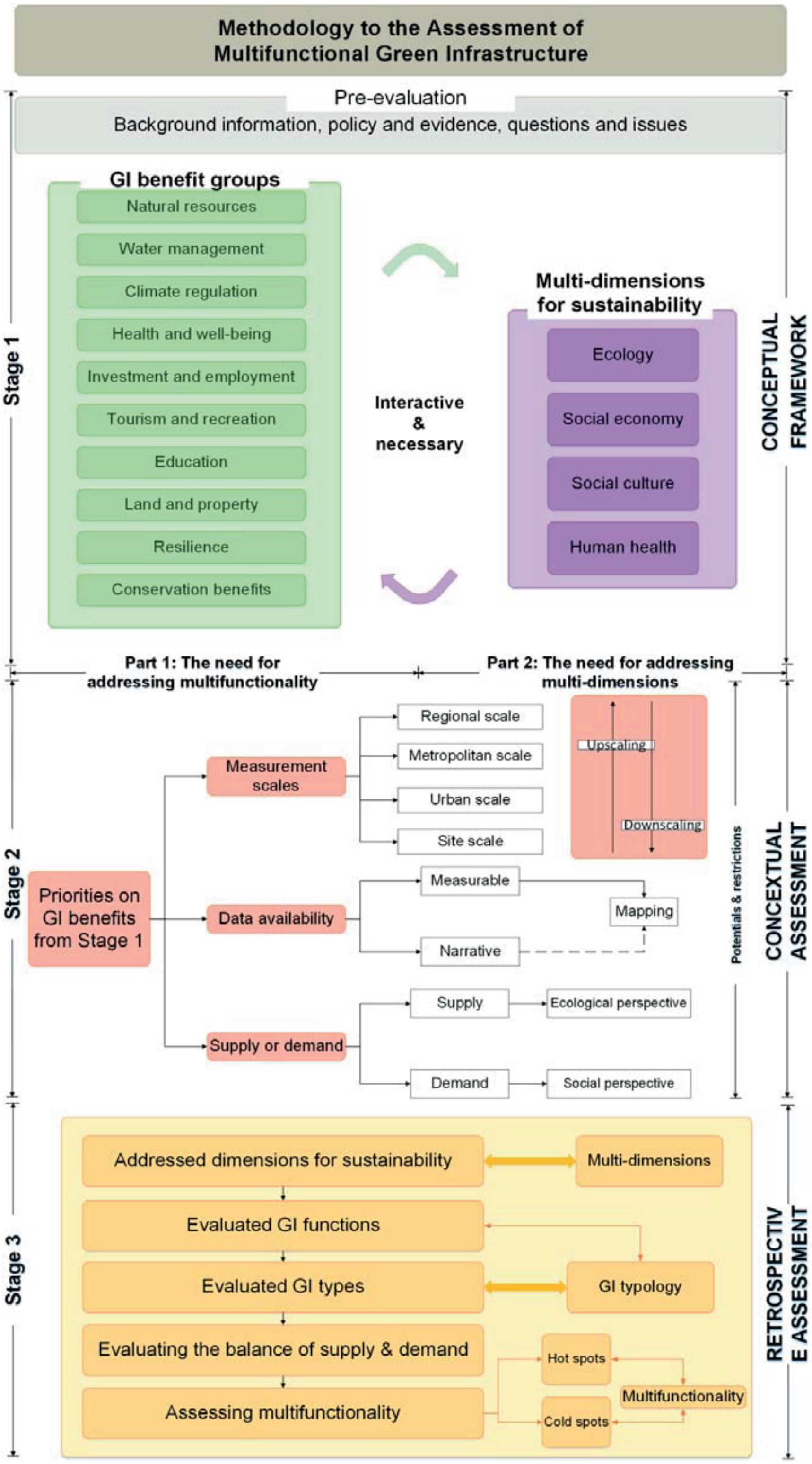

Figure 2. Flowchart on using the integrated indicator framework to conduct an AMGI.

Both the GI benefits and multi-dimensions of sustainability comprise the main content of conceptual framework. The background information for the collection of respective policy and evidence as well as research questions and planning issues in case studies are the first step of AMGI as the pre-evaluation for an AMGI. Furthermore, the reinforced pillars towards sustainability [13] comprise the dimensions ecology, social economy, social culture, and human health, and are also addressed in our approach. All of them underpin the pre-evaluation and priority settings.

However, it requires great effort to do the entire assessment at all scales simultaneously, since a large number of aspects (see Figure 2) should be considered: one has to prioritize focal scales depending on the purpose of the use of indicator-based framework. Is it to support a city-wide strategy or is it for planning tools at more detailed levels? Which criteria are vital, which spatial extent is meaningful, which data is available, or what have been investigated for an AMGI (either supply or demand of GI)? Conducting such an assessment is an intricate process, and therefore, we developed an integrative approach that allows us to derive three stages of evaluation, illustrated in a methodological workflow (Figure 2).

As Figure 2 shows, there are three stages while conducting an integrative assessment on multifunctional GI. They are:

(1) Stage 1: for priority setting, there are needs for addressing multifunctionality and the multi-dimensions of sustainability.

As a prerequisite of this stage, the key strategy and policy documents on spatial planning ought to be assessed as evidence for priority settings. At this first stage, users of an indicator framework should figure out their needs from two aspects. First, they should decide on the needs for addressing multifunctionality. Users could select the priorities of GI functions from our ten benefit groups (in the green box: from natural resources to conservation benefits). Second, it is suggested to be aware of the addressed multi-dimensions for sustainability (in the purple box: ecology, social economy, social culture, human health dimensions). Multi-dimensional analysis can be completed referring to the advice we provided in Tables A1–A3. In this conceptual framework phase, the emphasis on the multiple GI functions and multi-dimensions are interactive and necessary.

(2) Stage 2: for contextual assessment, there are needs to frame the indicator selection

Once we have the priorities of GI functions and aimed dimensions for sustainability, there will be three key factors on indicator selection (in the red color box). They are determinants for users' decision-making. To facilitate the decision-making while using our integrated framework, we provide related information in the Supplementary Materials. This information is not as comprehensive as to be applicable to all situations, because the selection of indicators depends on the research question, cultural context of the case study and related data availability. However, it still provides evident references and useful methodology that are of great significance.

In Stage 2, there must first be a scientific understanding for which spatial scale(s) is/are vital when assessing GI functions—focal scale. In our approach, we provide advice on four scales for spatially explicit indicators as references: regional, metropolitan, urban, and site scales (see the synthetic analysis in Supplementary Materials Text S1). For the purpose of covering integrative GI functions, GI assessment can be conducted at multi-scales, as long as users are aware of the potentials and restrictions (see Stage 2 in Figure 2). Due to indicator selections, these potentials and restrictions might be in the process of upscaling or downscaling, as well as limited by data availability in respective contexts. It is understandable to use the narrative method (qualitative assessment) to describe the GI functions or indicators when there is a lack of data in contextual assessment, or including upscaling or downscaling indicators as proxies. Although there is a thorough understanding of the balance between supply and demand, it might be vital for the sake of the study just to focus on one of the two aspects.

(3) Stage 3: for retrospective assessment, there are five major elements/components being advised to be evaluated again to exploit the multifunctionality of GI in depth.

These five elements correspond to five procedural questions for retrospection. They are: which kinds of GI functions have been evaluated? Another question deals with what kinds of GI types have been involved in the stage of contextual assessment compared to our comprehensive GI typology (see Appendix B, ordered by the intensity of human influence on GI), which is adapted from the urban GI Components Inventory from the Green Surge project [58]. Overall, through which dimensions has sustainability been addressed? What is the balance between supply and demand indicators in the particular contextual assessment? It is still scientifically sound that in the end evaluations could not reach a good balance due to limited data availability? It could be acceptable on the condition that the extracted results are well distinguished by either referring to the supply or demand of ESS. After completing the above-mentioned analysis, users are able to conclude the evaluated GI functions, their relationships with involved GI types, and the addressed multi-dimensions, and thereby figure out the multifunctioning GI in respective contexts.

To better understand and visualize the multifunctionality of GI, we suggest using measurable indicators in Stage 2. Using those, GI functions can be overlapped to explore whether one spatial unit provides multiple GI functions at the same time. These areas could be defined as multifunctional GI. The areas with three or more types of functions [59,60] could be defined as multifunctional GI hotspots using the method by Peng et al. [59] In other words, those units, e.g., grids, with three or more GI functions spatially form a range of high possibility clusters of GI functions.

To have insights into each GI function, we also recommend identifying the hot and cold spots of evaluated GI functions from Stage 2 in a respective contextual assessment. Therefore, one new index, namely the Getis Ord G_i* statistics, as one of the most widely used indicators of local spatial autocorrelation [59,61–63], is advised to detect the spatial aggregation of each GI function in terms of their spatial weight matrix, by identifying the respective GI within values higher than others as the hot spots and significantly lower than others as cold spots:

$$G_i^*(d) = \sum_{i=1}^{n} w_{ij}(d)x_j / \sum_{j=1}^{n} x_j \tag{1}$$

G_i* can be used to characterize the GI functions and their spatial correlations with the neighboring areas at a defined distance. In this equation, w_{ij} is symmetrically normed from one to zero as a spatial weight matrix, with one for all grids at a given distance d of cell i including the cell i itself, and zero for the other grids. In this case, the numerator is the sum of all the values of specific GI functions associated with the grids at the distance d of cell i, whereas the denominator is the sum of all the values of specific GI functions associated with all the grids. G_i* can be standardized as follows:

$$Z\left(G_i^*\right) = \frac{G_i^* - E\left(G_i^*\right)}{\sqrt{\mathrm{Var}\left(G_i^*\right)}} \tag{2}$$

where $E(G_i*)$ and Var(G_i*) are the mathematical expectation and variable coefficient of G_i*, respectively. For a grid, a significantly high positive Z score indicates that the values of its neighborhood grids are higher than the average with an apparent spatial concentration at a certain distance [61,62]. A Z score near zero refers to spatial dispersion. According to the indication of the Z score, the hot/cold spots of each GI function can be identified.

3.3. Remote Sensing-Based Methods in the Application in Leipzig

As preprocessing procedures for the AMGI in Leipzig, the Urban Atlas dataset (2012) [50], the biotope mapping (2005) [51] and local LULC dataset (2012) [54,55] were transformed into Geographic Coordinate System – European Terrestrial System – 1989 (GCS-ETRS-1989) with the Universal Transverse Mercator project (UTM-Zone-33N), given the small distortion and the popularity of the UTM system and the possibility of international comparison. All these georeferenced RS datasets were used to identify the enclosed GI features, thereby deriving respective indicators of various GI functions (Table 2). Based on these RS data, an overlay analysis of multifunctional GI areas was further undertaken to recognize the hot/cold spots areas. For the spatial analysis and methods for the identification, we followed the steps introduced in Section 3.2.

In the application of Leipzig, as shown in Figure 3, the Urban Atlas dataset (2012) [50] was used to obtain information on the population without urban green spaces within 500 m in their neighborhood using the RS-based method proposed by Poelman [64]. It was also used to resample the remotely sensed thermal data in Leipzig to evaluate the cooling effects of GI using the method introduced by Schwarz et al. [65]. In their paper, the thermal data refers to the land surface temperature acquired during the two overhead flights on 22 (7:30–9:00 p.m.) and 23 (5:00–6:30 a.m.), in September 2010 at 2000 m above the ground, within a spatial resolution of 5 m [65]. Substantial contributions to our application can be attributed to the biotope mapping (Figure 3), through which we could identify various GI types, urban recreational areas such as zoological and botanical gardens etc. to obtain respective indicators for the assessment of GI functions. As for the local LULC dataset, it was employed to assess GI benefits in water management, by providing its higher accuracy on the identification of water areas and green areas along with water courses.

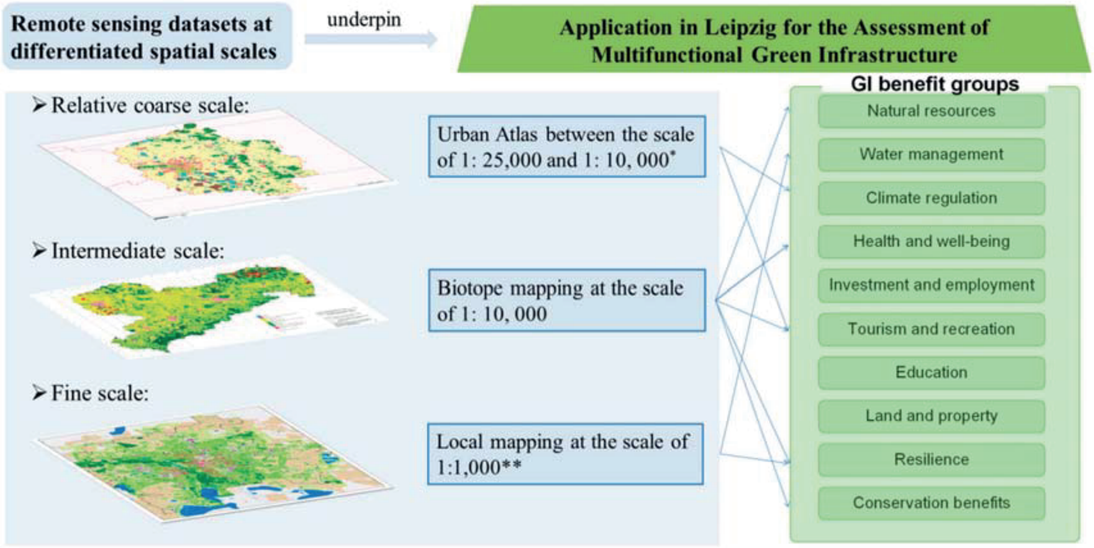

Figure 3. Remote sensing datasets from relative coarse, intermediate, to fine scale as supportive tools for the AMGI in Leipzig.

4. Results

In this section, we analyze the three aforementioned prominent frameworks I to III according to their structures, benefit groups, and data availability, as well as respective qualitative and quantitative measurements. To do so, we classified the different indicator frameworks with respect to the four central dimensions. The results for the multi-dimensional analysis are illustrated for each framework in the respective Appendix A. Furthermore, the relevant spatial extents of the indicators in each indicator framework are analyzed and depicted in the Supplementary Materials Figure S1. In order to understand if there is a kind of balance between supply and demand indicators, we examined their share in each of the frameworks as well, as shown in Figure S2.

In the following, we will first present our analytical results for each of the frameworks and then provide the synthesis in integrated framework for AMGI.

4.1. Multi-Dimensional Analysis of Indicator Frameworks I–III Towards Sustainability

4.1.1. Indicator Framework I for ESS Assessment from MAES

Indicator framework I (Table A1) is composed of 40 indicators. In total, one quarter of the indicators involves more than one dimension. To sum up, 52% of the indicators relate to the ecological dimension, 24% of the indicators relate to the socio-cultural dimension, 14% of the indicators refer to human health, and only 10% refer closely to the socio-economic dimension.

4.1.2. Indicator Framework II for GI Implementation from IEEP

The framework is composed of 39 indicators, which include not only those ESS provided by GI but also a range of GI benefit groups, e.g., GI benefits for human health and well-being, investment and employment, and so on (Table A2). As one example, employment resulting from GI initiatives is not an ESS, but a benefit provided by GI. Indicator framework II has great potential for the AMGI on the grounds that it contains a wide range of GI benefits and comprehensively reflects GI functions. Likewise, we list indicator framework II regarding the four dimensions of sustainability (Table A2). A total of 40% of indicators are involved in more than one dimension. In sum, 45% of indicators relate to the ecological dimension, 22% refer to health, i.e., human health, 21% relate to the socio-economic dimension, and only 12% closely refer to the socio-cultural dimension.

4.1.3. Indicator Framework III Supporting a Shift towards a Green Economy from EMDA

In Table A3, there are 37 indicators for GI valuation derived primarily from the indicator framework GI Valuation Toolkit [26]. The analysis of indicator framework III shows that 68% of all indicators belong to more than one dimension of urban sustainability. That is to say, compared to indicator framework I and II, it has the highest percentage of indicators addressing multi-dimensions of sustainability. In detail, 35% of indicators relate to the socio-economic dimension, 29% relate to the ecological dimension, 20% refer to human health, and 17% closely refer to the socio-cultural dimension.

4.2. Integrated Indicator Framework for AMGI

The three chosen indicator frameworks were compared to analyze their potential coverage of the four sustainability dimensions, as well as further relevant characteristics for the assessment of multifunctional GI. Figure 4 depicts their share of multiple dimensions for sustainable urban development. Indicator framework I clearly emphasizes the ecological dimension, while indicator framework II is relatively weak with regards to the socio-cultural dimension, but covers the dimension of human health well-being. Indicator framework III strongly supports the socio-economic dimension of GI. It may hence be concluded that the three indicator frameworks can contribute in specific ways to a more integrative indicator framework for AMGI while also showing limitations.

As one important conclusion, these three frameworks are complementary within their special focus on various scales and dimensions. Therefore, we make full use of their contributions and adapt their dimensions and aspects to our integrated indicator framework, which is a multi-scale and multi-dimensional indicator database (Appendix A). This synopsis enables us to integrate their beneficial contributions to just one framework as our indicator pool to undertake an AMGI.

The comparison results on the relevant spatial extents (Figure S1) as well as the percentages of supply/demand indicators (Figure S2) from indicator framework I to III, and the respective information (Text S1) are provided in Supplementary Materials to facilitate the potential applications of our methodology. Our approach is sensitive to criteria such as spatial scales and data availability, and therefore not applicable to all situations. However, it is the first time that such an explicit indicator framework has been proposed for AMGI while including multi-dimensional analysis for sustainability. This result helps ensure the constancy of GI assessment as well as combine and scale up the research on AMGI. A major restriction of potential applications of our integrated framework is data availability in certain cultural contexts.

As synoptic findings, we concluded that there is potential to conduct AMGI at multiple scales, but substantial data gaps remain to be filled before a fully integrated and complete GI assessment can be carried out. Conclusively, applied studies at multiple scales are needed to manifest the usefulness of our AMGI framework as well as reinforce it in practice. We hence deployed the process of indicator selection in the following section and thereby present the validation of indicators from our integrated framework, guided by the methodology flowchart in Section 3.2 (Figure 2).

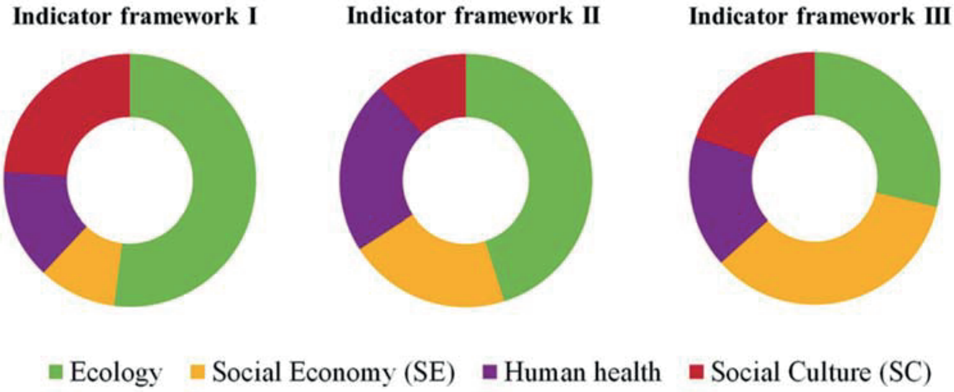

Figure 4. Indicator framework I to III in terms of ecological, socio-cultural, socio-economic, and human health dimensions.

4.3. Exemplification of an Assessment of Multifunctional Green Infrastructure (AMGI)

In this Section, we give an illustrative case of AMGI at urban scale to validate the methodology advised in Section 2. We conducted this case in the City of Leipzig, Germany, and got the following results (from Stage 1 to 3).

(1) Stage 1: The needs for addressing multifunctionality and multi-dimensions of sustainability.

As a pre-evaluation, we give brief information on our study area to facilitate our workflow from Stage 1 to 3 according to the work flow in Figure 2. Our study site is Leipzig, Germany, which covers an area of 298 km^2, is home to 596,517 inhabitants in 2018 [56] and is characterized by a multitude of high-density built-up areas in Figure 5. In the last five years, Leipzig has been the fastest growing city in Germany, signifying high pressure on urban GI through housing development and the need for more public infrastructure. Physiographically, the city has one of the most extensive alluvial forests in Europe. When further depicting the local GI, it is furnished by long-term urban community gardens and allotments with one of the highest spatial expansions in Germany. Both of them should be reflected in AMGI.

For our priority settings, we intend to address the needs of ten GI benefits regarding how to use our approach. In addition to considerations on data availability, our principle provides at least one example for each of the GI benefits to illustrate the usage of the proposed framework and methodological guideline.

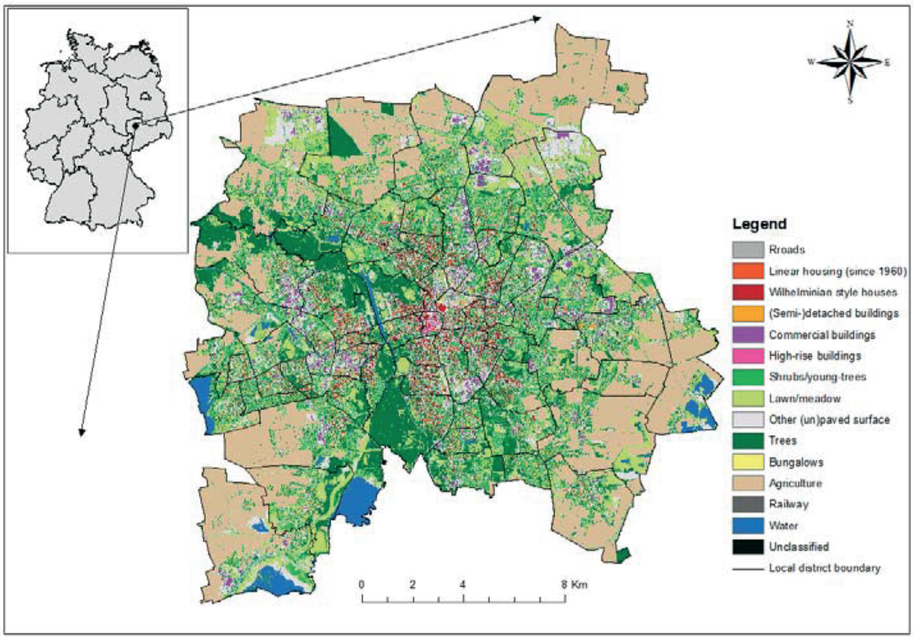

Figure 5. The location and Land Use and Cover map of the illustrative case at urban scale, in the City of Leipzig, Germany.

(2) Stage 2: Contextual assessment in the City of Leipzig, Germany

The assessment is conducted in Leipzig on the basis of preprocessing in Stage 1. We set our focus on the urban scale (Figure 5), and concentrate primarily on the capacity of GI benefits. The selected indicators and analysis can be found in Table 2. Indicators that are not available in the study area are marked as N/A, and we highlight potential methods and references, respectively. For example, indicators such as No. 00029 (number of visitors to protected sites per year) and No. 00030 (number of local users for hiking, camping, nature walks, and jogging) etc. are not available at the whole urban scale; however, we itemize newly developed methods, e.g., smartphone apps, namely the Mapping Nature's services (MapNat) app [66].

The contextual assessment leads to a lean indicator framework as shown in Figure 6, guided by our workflow in Figure 3. The selected indicators are defined in Figure 6 and Table 2, evaluated either quantitatively as measurements or qualitatively as a description.

Regarding the contextual assessment, we summarized the evaluation results of GI benefits for the whole urban area (see Table 2), which are aggregated to the urban scale. We can conclude that GI provides natural resources, such as carbon storage 11.8 MgC/ha on average [67,68] and water surfaces account for 2.5% of the whole municipal space. GI function can be reflected from around 13 ha (0.04%) wetlands and 41 ha (0.14%) vegetation alongside water bodies to regulate surface runoff water. They are identified and mapped as river-related GI in Figure 6 to show the GI capacity of water regulation.

For the multifunctioning GI, there are several GI elements worth being highlighted in Leipzig. For example, there are around 28.2 m^2 allotments and community gardens per inhabitant. They are not only for food self-supply but also form important parts of recreational spaces. Both of them are evaluated and reflected in Figures 7 and 8. In total, there are around 70 m^2 recreational spaces for each inhabitant, encompassing gardens, parks, urban forests, allotments, sports and leisure facilities, zoological and botanical gardens, and so forth, which are widely dispersed in the city. Another multifunctional GI is dedicated to the urban alluvial forests (see Figures 5 and 8), in total 1033 ha in Leipzig. They are not only recreational areas for urban dwellers but, in addition, they have special value for habitat, species, and genetic diversity. In this case, they can be marked as having a special conservation function (i.e., neither associated with the actual use of ecosystems, nor to its potential use in the future) for sustainable development and future generations [26]. Its existence ought to be protected as its primary function (see in Figure 7).

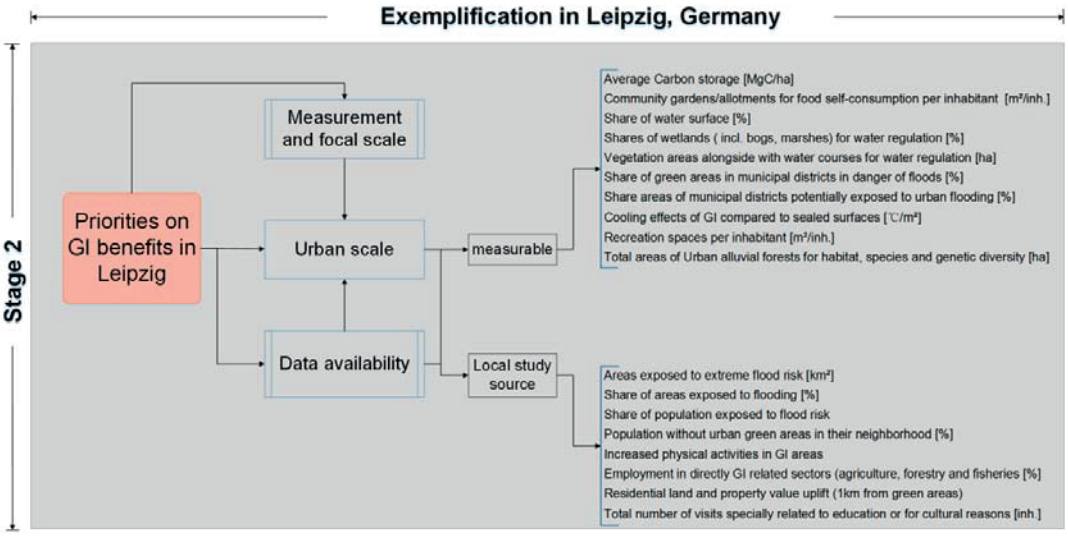

Figure 6. Results from indicator selections for the illustrative case in Leipzig, Germany.

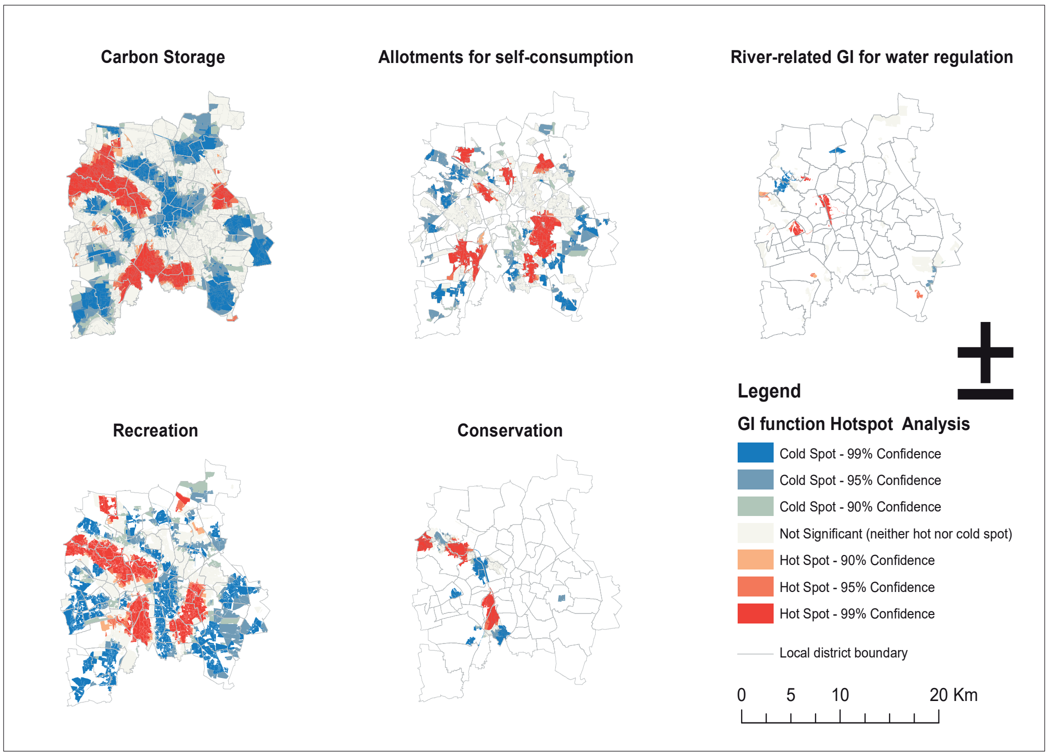

Figure 7. Spatial distributions of hot/cold spots of GI functions.

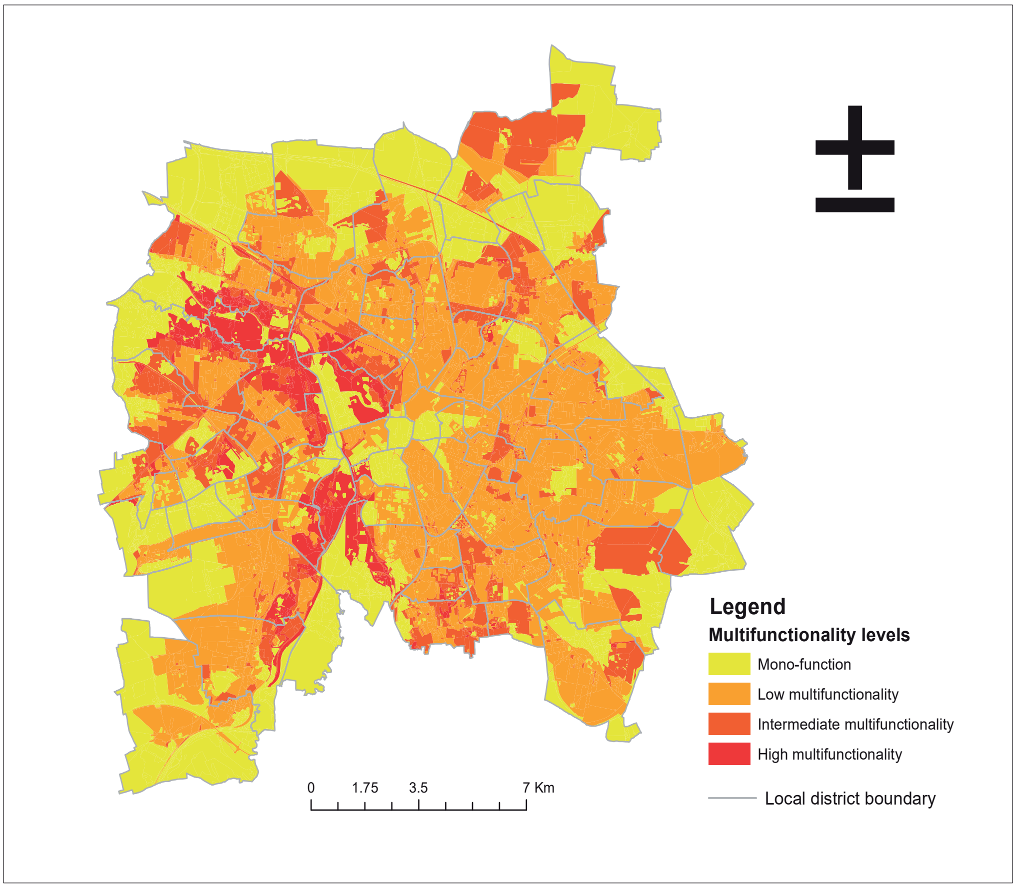

Figure 8. Spatial distribution of GI multifunctionality in Leipzig, Germany.

Regarding resilience against exposure to urban flooding, we find a share of 57% of green spaces in local districts exposed to flooding. That is of special concern where rivers are running through adjacent to built-up areas, of which Leipzig possessed a multitude, such as White Elster, Pleiße, Parthe [69]. Complementarily, a local case study by Kubal et al. (2009) [70] concluded that there are about 45 km^2 areas, i.e., 15% of the city exposed to extreme flood risk. As for the GI function related to local climate change, the urban GI provides nearly 0.25 °C/m^2 of cooling effects [65], compared to the sealed surfaces. Thus, the further the distance to local GI, the larger the exposureo urban heat island effects. To reflect the GI function in the support of employment, we find that GI elements such as agriculture, forest and fisheries provide an employment rate of about 13.7% in the study area.

Table 2. A lean indicator framework to exemplify AMGI, adapted and selected from integrated framework.

Indicator & Unit	Data Base	Data Type	Method/Source	Values
Average Carbon storage (MgC/ha)	Biotope mapping	Polygon	Analysis and extraction from Strohbach and Haase (2012) [67], and Derkzen et al. (2015) [68]	11.80
Community gardens/allotments for food self-consumption per inhabitant (m^2/inhabitant (inh.).)	Biotope mapping	Polygon	Calculation and aggregation *	28.20
Share of water surface (%)	Local Land Use and Cover map	Polygon	Calculation and aggregation *	2.50
Shares of wetlands for water regulation (%)	Biotope mapping	Polygon	Calculation and aggregation *	0.04
Vegetation areas alongside with water courses for water regulation (ha)	Biotope mapping	Polygon	Identification and calculation	0.14
Share of green areas in municipal districts in danger of floods (%)	Biotope mapping	Polygon	Calculation and aggregation	56.65
Share areas of municipal districts potentially exposed to urban flooding (%)	Biotope mapping	Polygon	Calculation and aggregation	42.83
Cooling effects of GI compared to sealed surfaces (°C/m^2)	Urban Atlas	Raster	Analysis and extraction from Schwarz et al. (2012) [65]	0.25
Recreation spaces per inhabitant (m^2/inh.)	Biotope mapping	Polygon	Calculation and aggregation *	69.51
Total areas of urban alluvial forests for habitat, species and genetic diversity (ha)	Biotope mapping	Polygon	Identification and calculation *	1033.00
Areas exposed to extreme flood risk (km^2)	Local case study	-	Data from Kubal et al. (2009) [70]	45.00
Share of areas exposed to flooding (%)	Local case study	Polygon	Data from Kubal et al. (2009) [70]	8.00
Share of population exposed to flood risk	Biotope mapping	Polygon	Calculation and aggregation	46.18
Population without urban green spaces in their neighborhood (%)	Urban Atlas,	Polygon	Method newly introduced by Poelman [64]	2.37
Increased physical activities in GI areas	Field surveys	Point	Observation and survey	N/A
Employment in directly GI related sectors (agriculture, forestry, and fisheries (%)	Sachsen Statistics [71]	-	Statistik der Bundesagentur für Arbeit [72]	13.70
Residential land and property increment value (1 km from green areas)	Wohnungsbörse Leipzig [73]	-	Literature [74]	N/A
Total number of visits specially related to education or for cultural reasons (inh.)	Statistics	-	Literature	N/A

* This indicator was adapted and further used for GI function mapping to identify the spatial distribution of hotspots of GI functions.

With respect to external benefits due to the development of GI, the increment values of both ground land [74] and apartment rent [73] imply a GI function on investment, since we observe an increase of both with an increasing proximity to GI. Hence, we detect hotspot areas of GI on the recreational function map (Figure 7). Likely, the 'good' (standard ground value from 280–400 €/m^2) and 'super good' (above 400 €/m^2) lands are nearby the parks and urban alluvial forests. Detailed results are presented in Table 2.

Among results in Figure 6, GI functions (the above-ground carbon storage, allotments producing food for self-consumption, river-related GI for water regulation, recreation function, and special conservation benefits of GI for habitat, species and generic diversity) can be further illustrated by calculating the Getis Ord G_i* index (see Section 3). The calculated results served to identify the spatial patterns of the hot/cold spots of each GI function in Figure 7. Both the hot spots and cold spots of GI functions are allocated all over the city. There are no regular patterns among different functions. The resulting maps show variation in GI functions over space. However, it can be concluded that there is a specific spatial concentration of the recreation function in the central western part of Leipzig, which proves that the multifunctionality of the urban forest alluvial plays a significant role for residents in Leipzig.

These five GI functions are overlaid to identify the multifunctionality of GI in this case study (Figure 8). The results show different intensities of multifunctionality: mono-function, low, intermediate and high levels of multifunctionality displayed in Figure 8. Combined with Figure 7, the spatial distributions of multifunctionality (Figure 8) present the complex urban ecosystems of different GI functions in relation to the spatially heterogeneous multifunctional GI. There are no inevitable connections between hot spot areas and multifunctional areas. What is important is that the multifunctional areas generally cross the local district boundaries. From the city center to outskirts, the level of multifunctionality is diverse and slightly inclined to the mono-function direction that is first assigned to agricultural land.

(3) Stage 3: For the retrospective assessment, we re-evaluated our illustrative case according to guiding questions in Section 3 (Figure 9 in the yellow box).

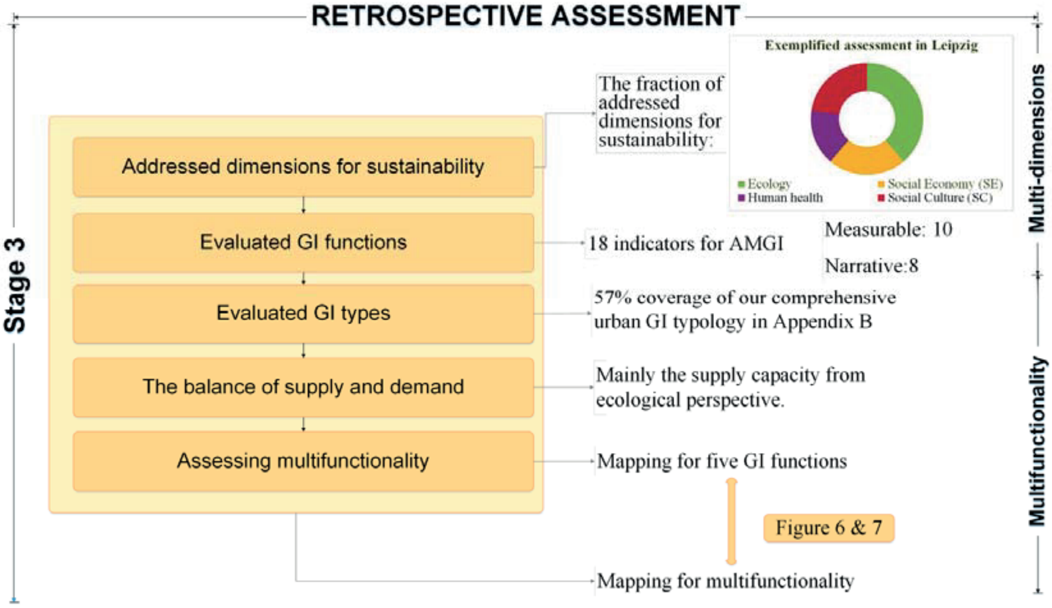

Figure 9. The results of Stage 3 exemplified in Leipzig.

Concerning retrospective assessment, the results are presented in Figure 9. For the four dimensions of urban sustainable development, the selected indicators convey four dimensions and their fractions do not show apparent bias: ecology (39%), socio-economy (23%), socio-culture (16%), and human health (23%) (see the fraction circle in Figure 9). However, they show great restrictions on the socio-economic dimension due to a lack of data availability. Overall, we employ 18 indicators in total, and the GI types encompassed in our AMGI analysis are checked and compared with our comprehensive GI typology adapted from the urban GI Components Inventory of the Green Surge project [58] and marked as YES/NO in the last column (Table A4).

5. Discussion

5.1. Evaluation of Our Integrated Indicator Framework

When comparing and analyzing indicator frameworks I to III, we revealed the potential contributions of these frameworks to the conceptual development of GI. It enabled us to develop an integrated framework and methodology for AMGI, accounting for the urban sustainability dimensions of ecology, socio-economy, socio-culture, and human health. Thus, our indicator-based framework advances a more complex analysis of GI through the incorporation of a multi-dimensional analysis towards sustainability as well as the provision of ten GI benefits that potentially facilitate the capture of multiple GI functions. The strength of our proposed framework is to provide an easy to handle pool of indicators (Appendix A) for a comprehensive urban GI typology (Appendix B), as well as an illustrative methodology (Figure 2) for further applications in AMGI. The integrated indicator framework and assessment methodology both form an informative toolbox to undertake an integrative GI assessment.

Previously, AMGI was regarded as an intricate process, because not only the diversity and uncertainty of the GI concept itself [1,3,75] but also the multiple functions of GI seemed hard to capture fully [1,3]. Compared with the conceptual framework for multifunctionality in GI planning for urban areas by Hansen and Pauleit [76], this study supplies an indicator-based framework and a holistic GI assessment methodology, while setting the multifunctionality of GI as one given assumption. Both the framework for multifunctionality in GI planning by Hansen and Pauleit [76] and our framework in this paper have reinforced the significance of GI planning from the ecological and social perspective. As one potential novelty, the latter has underscored these two perspectives by taking indicators as proxies and classifying each indicator in terms of ecological, socio-economic, socio-cultural, and human health dimensions. However, our indicator-based framework made the coverage of multiple GI functions and the incorporation of the latest conceptual evolution of GI the first priorities and thus little attention was paid to the synergies and trade-offs amongst different GI functions and the stakeholder preferences [76]. However, the latter are of great importance for multifunctionality assessment of GI and it ought to be further analyzed based on this integrated indicator framework.

Although we have stated that ESS provided by GI, the multiple benefits and functions of GI, and a potential shift towards a green economy are three major aspects of GI assessment, we could only address the former two in our exemplification. However, our framework would allow one to address the green economy dimension by including indicators such as employment in directly GI-related sectors (agriculture, forestry, and fisheries), and the increment economic values of residential land and property 1 km from green areas [77] to emphasize the significance of a shift towards a green economy [32]. As for the question whether the enclosed indicators are applicable, measurable, or even transferable, further analyses and potential compromises on indicator selections must be carried out with respect to different cultural contexts. For instance, to assess urban biodiversity, indicators such as the capacity of ecosystems to sustain insect pollinators' activity has up to now only been available at European scale from the ecosystem services mapping at European scale (ESTIMAP) [77,78]. The respective method for ecological modeling for an urban evaluation, i.e., the urban version of the ESTIMAP-P [79] model for pollination, is still under development, because an adaption of LULC and the distance to semi-natural vegetation patches [79] call for a high quality of RS information to capture the spatial heterogeneity in urban settings. From this viewpoint, we state that RS information have been shown in this study to be extremely supportive for GI assessment and planning.

5.2. Implications from the AMGI Exemplified in One European City, Leipzig

The AMGI exemplified in one European city implies substantial contributions to the GI assessment and planning, and simultaneously may inspire RS experts and Geographic Information System (GIS) scholars from various disciplines.

For the GI assessment and planning, we provide a number of indicators to capture multiple GI functions in urban areas such as carbon storage from green areas, allotments and community gardens for food self-supply, river-adjacent GI for water regulation, and recreation spaces. The approach helped to identify the hot/cold spots for these different GI functions as well as the spatially aggregated multifunctional areas instead of isolated grid cells with high values of GI functions [59,80].

In hotspot areas, the values of respective GI functions are significantly higher than the average [81]. This information may facilitate the GI planning by easily identifying sites/areas within higher multifunctionality, whereas at locations recognized as cold spots, potential GI plans such as being accessible to recreation (walking, jogging) to promote human health and well-being, or planting street trees for urban heat island mitigation, may be advised to increase the multifunctionality of GI. In our exemplification of Leipzig, we observed a large percentage of multifunctional GI crossing municipal districts in Figure 8. For the GI assessment and planning in the City of Leipzig, it demonstrates an apparent demand of collaborations beyond local districts, especially for those local districts in the west of the city center like Grünau, Schönau, Neulidennau, and Leutzsch, to realize the multifunctionality of GI. Therefore, green space planning and management should go across the barriers of administrative boundaries and the spatial relations of multiple GI functions to establish multifunctional networks of GI.

Overall, the application of the AMGI framework enabled us to identify and assess 26 types of GI elements in total. Compared with our GI typology (listed according to the intensity of human influence/association with GI in Table A4), our analysis covers 57% GI types of the whole typology. Before, GI was analyzed either limited to some types with few connections to GI functions or only associated with one or two functions [3,4,82]. However, a limitation of our exemplification is that due to the conceptual and methodological focus of the study, we were not able to explore in more depth the synergies and trade-offs of GI in relation to various local policies and strategies. Moreover, the weighting of the various GI functions for a contextualized assessment of multifunctionality was not feasible, due to the lack of information on the preferences of different stakeholders [32,76]. Therefore, in our application, we mainly focus on the supply of ESS provided by GI, instead of the demand of ESS. Additionally, we primarily included indicators covering the ecological and socio-cultural dimensions, but very few from the socio-economic and human health dimensions. The latter was mainly due to limited data availability.

Nonetheless, it is exactly these restrictions reflected in our exemplification that show the substantial demand of interdisciplinary and transdisciplinary research and collaborations, particularly amongst RS experts and GIS scientists. When we tested the applicability of our assessment framework to a European city, we recognized the necessity for AMGI using remote sensing-based methods. Thus, this paper is expected to draw attention to the strengthening of the urban GI assessment using RS-based and GIS-based methods. From this point of view, the proposed integrated framework, and its application in this paper will help foster the creation of a common language for better mutual understanding amongst scientists and stakeholders, given that a clear framework is crucial for the sustainable management of spatially-oriented GI plans over time and along various stakeholder groups. It is quite challenging for a GI assessment and planning but essential to further explorations to enhance the synergies and reduce the trade-offs [76] of multiple GI functions.

5.3. Application Potential of Our Integrated Indicator Framework and Methodology

Exemplifying the assessment approach can help to better understand our indicator framework and methodology, which foster or hinder the AMGI in different contexts. For the purpose of a clear illustration and full exploration of our framework while exemplifying in Leipzig, we selected at least one indicator for each GI benefit. In the process of running the whole methodology (from stage 1 to 3) in one European city, we found that the application of our integrated framework calls for a comprehensive review of local studies (e.g., [65,67,70]) and an extensive understanding of spatial datasets for the AMGI. For example, our selection of earth observation datasets, i.e., Urban Atlas data, biotope mapping, and local LULC data, was built on an underlying analysis considering their contributions to AMGI and taking the spatial resolution of each and their respective classification of urban spatial categories (at least to their secondary classes) into account. Therefore, the methodology in this paper can be applied to other European cities and also inspires other cities with similar remote sensing information.

Publicly available RS datasets, e.g., CORINE and Urban Atlas datasets [50] delivered by the European Environment Agency (EEA) and the European Commission DG Joint Research Centre (JRC) (https://land.copernicus.eu/), aid in the transferability of our methodology of GI assessment at a broader extent, since these datasets cover almost 39 countries in Europe. Moreover, biotope mapping has been shown to make a substantial contribution for AMGI at urban scale, given that it has contributed to an evaluation of GI benefits in natural resource, tourism and recreation, and conservation benefits. Therefore, for the areas where there is biotope mapping on the basis of investigations of individual habitats [48], there is higher potential behind the use of our methodology. For the cities where there are spatial datasets at high spatial resolution, likely the LULC data of Leipzig (2012) derived from OBIA approach [54,55] , our framework and assessment methodology would show value, since both of them are ready to be applied to other cities and have proven to be valid to identify the hotspots of respective GI functions as well as the multifunctional areas. Moreover, the indicator Getis Ord Gi* we chose in the methodology for the identification of hot/cold spots of GI functions is not limited to the urban scale. It could be used at various scales such as regional, metropolitan, and local scales as well. Accordingly, the earth observation data and the simple and efficient method for hotspot analysis both contribute to the potential applications of our framework and methodology.

5.4. Improving the Integrated Framework on AMGI and Its Limitations

To inspire and provoke more studies for improving AMGI in practice, we argue that there are two dimensions of the multifunctionality of GI. The first dimension is the multiple functions within one specific area. The second dimension refers to the functions of GI at multiple scales and varied interconnected roles of GI as networks to enhance structural and functional connectivity. This paper only covered the first dimension by considering as many GI functions as possible without exploring the synergies among multiple GI functions. Thus, a limitation of this study is exploring the structural and functional connectivity. Nonetheless, this paper provides an essential basis for it by presenting an integrative indicator framework for AMGI as well as exemplifying its usage in Leipzig. As for potential synergies and trade-offs, a comparative analysis should be undertaken, including different spatial changes over a certain time span. It limits our research findings that we could not include long-term synergies and trade-offs. The spatial and temporal changes of multifunctional GI would be a significant direction to work on in the near future.

This promising direction requires high-quality earth observation datasets, such as the upcoming Copernicus data, e.g., RS data on biosphere (the fraction of photosynthetically active radiation absorbed by the vegetation) and on oceanography (Lake Surface Water temperature (LSWT) at the spatial scales from 1 km, 300 m or even smaller), to disclose substantial GI functions that are not yet available in applications albeit already proposed in our integrated framework.

It necessitates the combination of remote sensing-based methods and GIS-based methods at various spatial, temporal, and spectral scales to support multifunctional GI analysis. For instance, incorporating leaf area index (LAI) at a global scale, i.e., remote sensing-based method using improved

Moderate Resolution Imaging Spectroradiometer (MODIS) LAI product at 1 km spatial resolution [83]. Likewise, evaluating leaf area density (LAD) at local scale, i.e., RS and GIS-based method using high-resolution terrestrial LiDAR—Terrestrial light detection and ranging (LiDAR) [84] to retrieve the three-dimensional (3D) structure properties of vegetation. Therefore, remote sensing-based methods would considerably contribute to the obtaining of respective indicators and the evaluation of GI functions in reduced water-off and cooling effects. Integrating the 3D information to enrich indicators for GI assessment and planning is likely to be one of the key topics in further multifunctional GI research.

6. Conclusions

Our study delivers an initial approach to conduct AMGI within a spatially explicit methodology. While providing an integrated indicator framework, we intend to draw attention to address ESS provided by GI, the multiple benefits and functions of GI, and a potential shift towards a green economy while conducting an AMGI at various spatial, temporal and spectral scales. We hence advise one fulfills an assessment using our framework and methodology following the three stages: (i) conceptual framework for priority settings to evaluate the needs for addressing multi-dimensions for sustainability and multifunctionality; (ii) contextual assessment considering focal scale, data availability; (iii) retrospective assessment: trace back to the whole process when the respective AMGI is completed. As an illustrative case, we present the exemplification of AMGI in Leipzig, Germany. In this case, we presented the application of our proposed framework, providing at least one example for each GI benefit. With our methodology, we make quite the positive experience using remotely sensed information for which we recommend that scholars could turn to our approach. Our toolbox is an appealing basis for multifunctional GI assessment. It can serve as the baseline for AMGI applications in other cultural contexts. Our research intends to push forward multi-scale research for the assessment of multiple GI functions and also to sow one seed of promoting multiple remote sensing-based methods when acquiring spatial indicators for GI functions and, by doing so, to advance urban GI further.

Supplementary Materials: The following are available online at http://www.mdpi.com/2072-4292/11/16/1869/s1, Figure S1: Relevant spatial extents of indicators from indicator framework I to III, Figure S2: The percentages of supply and demand indicators from indicator framework I to III, Text S1: Synthetic evaluation of indicator framework I to III.

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Appendix A

Multi-dimensional analysis of indicator frameworks I—III towards sustainability.

- Table A1: Indicator framework I for ESS assessment from MAES classified in terms of four dimensions.
- Table A2: Indicator framework II for GI implementation from IEEP classified in terms of four dimensions.
- Table A3: Indicator framework III for a shift towards green economy from EMDA classified in terms of four dimensions.

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remote sensing

Article

An Integrated Indicator Framework for the Assessment of Multifunctional Green Infrastructure — Exemplified in a European City

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List of supporting materials

- Text S1: Synthetic evaluation of indicator framework I to III
- Figure S1: Relevant spatial extents of indicators from indicator framework I to III
- Figure S2: The percentages of supply and demand indicators from indicator framework I to III

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Text S1: Synthetic evaluation of indicator framework I to III, Figure S1: Relevant spatial extents of indicators from indicator framework I to III, Figure S2: The percentages of supply and demand indicators from indicator framework I to III.

Text S1. Synthetic evaluation of indicator framework I to III

These three indicator frameworks are also distinct considering further important aspects when applying in an assessment of multifunctional GI: 1) relevant spatial extent, 2) involved GI types (service provision units), 3) data availability, 4) their information regarding GI assessment (e.g. data sources and references/proved methods) and 5) whether it is a supply indicator or a demand indicator.

For the **relevant spatial** extent, the hierarchical system of NUTS [1] was taken (Nomenclature des Unités Territoriales Statistiques). It was generated by the EU to identify and classify the spatial units of the official statistics in all member countries. A distinction can be made between the regional scales R (NUTS 2; i.e. the basic region, and NUTS 3 is the smaller regional level; more details see Appendix S.1). Further differentiation refers to the EU-OECD functional urban area definition M (metropolitan scale and to the spatial database provided), U (urban scale, i.e. municipality) and S (site scale: site-based small scale, where only single site data is available). Fig. S1 shows that the spatial scales of each indicator from indicator framework I to III emphasize different scales. **Indicator framework I** mostly refers to the metropolitan and urban scales [2]. By searches on databases *(Web of Science, Scopus and Google scholar)* of all indicators and the analysis of each indicator and their respective scales one by one, we find that **indicator framework II** mainly addresses site and local scales, and **indicator framework III** presents mostly the site scale. For the latter our result shows that approximately 80% cannot be valued at the regional and metropolitan scales.

At these spatial scales, different datasets can be used to fulfil the AMGI: (i) Corine Land Cover (CLC) and High Resolution Layers (HRL) which enclose forests, grasslands, imperviousness zones, permanent water bodies and wetlands in Europe; (ii) national level, e.g. Natura 2000 (N2K) across 28 EU nations; (iii) the state or municipal level, e.g. Urban Atlas (UA) datasets and biotope mapping. AMGI will benefit from multiple spatial scales but it should not limit in the datasets we mentioned in this paper. More research ought to be engaged to bring higher resolution or even 3D datasets into GI assessment.

As to **whether it is a supply indicator or a demand indicator**, crucial parts when assessing multifunctional GI are assigning indicators to either supply (capacity) or demand of GI. Therefore each indicator from indicator framework I to III is associated to the one or the other. In total, the percentages of indicators from these three prominent frameworks are different (Fig. S2). In **indicator framework I** and **II**, more than 50% of indicators reflect the supply of GI from the ecological perspective. However, in **indicator framework III**, there are more demand indicators. From this perspective, indicators in **indicator framework III** enrich the demand indicators in our indicators pool.

Overall, conducting AMGI at multiple spatial scales is important to fully capture the benefits of GI and understand the interlinkages between GI at these scales. However, it is a big effort to do the entire assessment at all scales simultaneously, since a large number of compromises and conflicts should be handled according to above-mentioned aspects. One has to prioritize certain scales depending on the purpose of the use of the results. Is it to support a city wide strategy or is it for planning at more detailed levels, its spatial extent, data availability or the focus on supply or demand of GI will be determinants for AMGI deploying these results.

As common ground, these three frameworks have enhanced the development of GI concept and foster realization of GI assessment in urban areas from different aspects, shown in Figure 5. The multi-dimensional analysis underpins the individual contributions to the GI concept of these three indicator frameworks, i.e. **indicator framework I** contributes to inclusion of comprehensive ESS provided by GI, especially within a highly urban focus; **indicator framework II** provides multiple GI benefit groups and incorporates more human health aspects; **indicator framework III** is composed of more monetary valuated indicators and therefore potentially facilitates GI concept towards a shift in green economy. We hence suggest enclosing indicator framework I to III while undertaking an individual AMGI.

Figure S1: Relevant spatial extents of indicators from indicator framework I to III

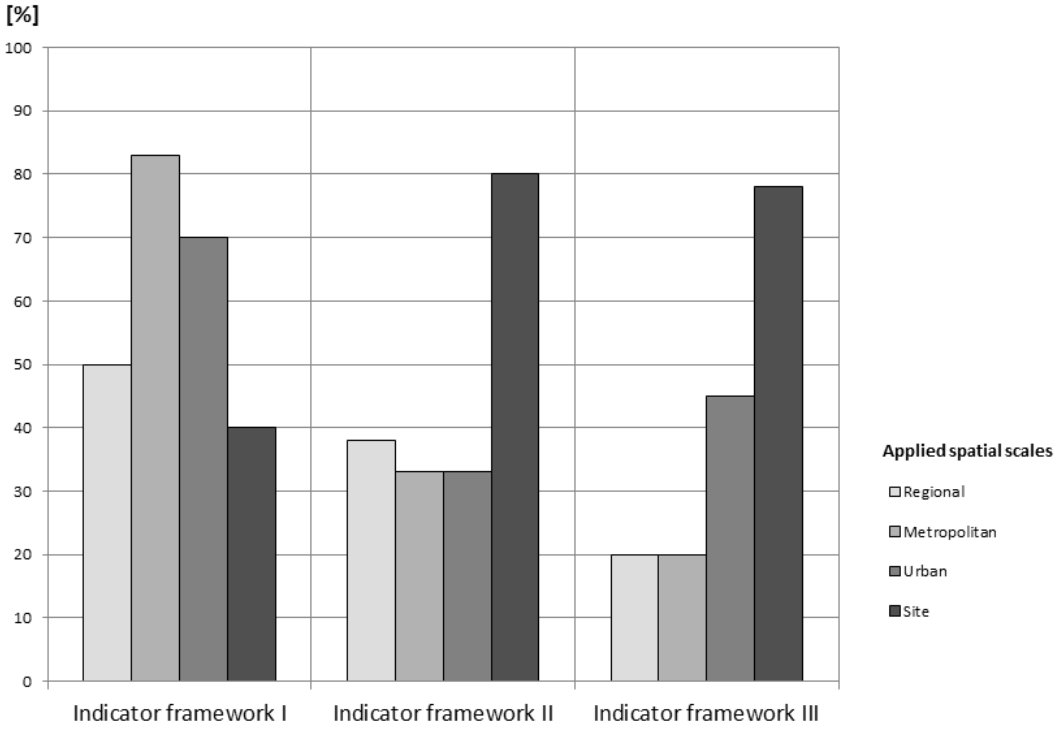

Figure S1 Relevant spatial extents of indicators from indicator framework I to III

Figure S2: The percentages of supply and demand indicators from indicator framework I to III

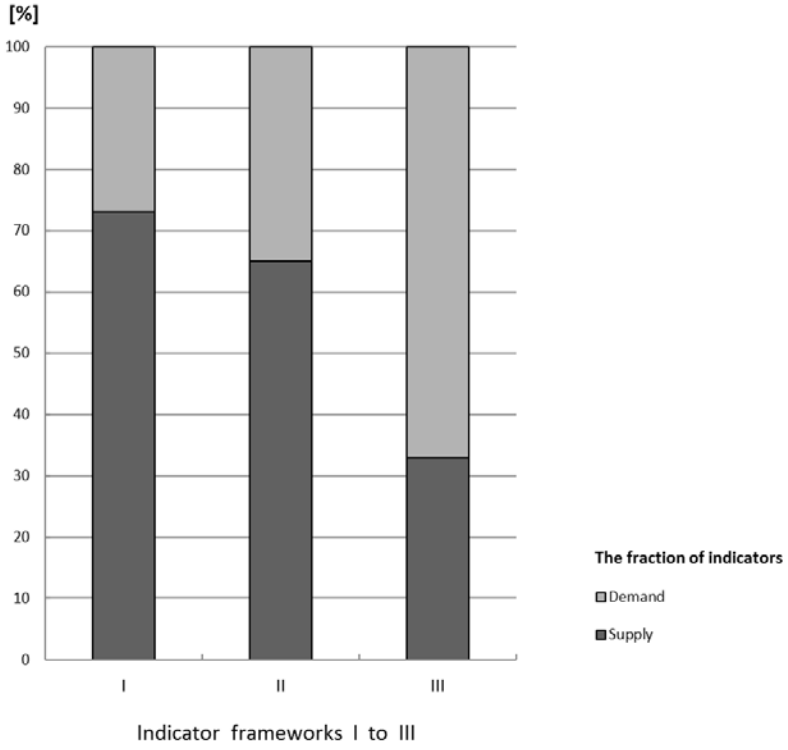

Figure S2 The percentages of supply and demand indicators from indicator framework I to III

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Paper III

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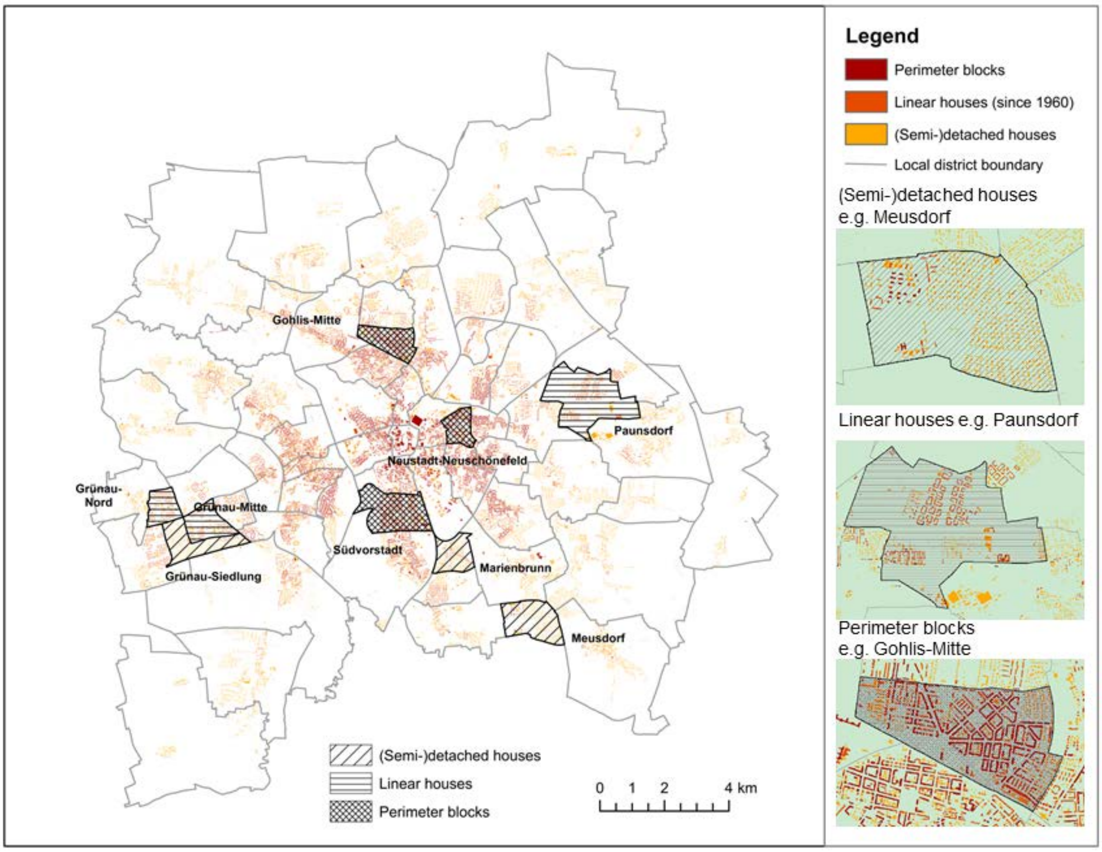

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Spatial patterns of urban green infrastructure for equity: A novel exploration

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ABSTRACT

Urbanization processes spur the need for urban green infrastructure (GI) to support the well-being of urban dwellers and underpin a sustainable planning strategy. It is a challenge for urban planning to make cities equitable in a socio-spatial way for which strategic planning are demanded based on measured gradients of spatial equity for GI. Strategically, urban GI planning should pay tribute to the inherent spatial patterns and foster a fair distribution of GI towards spatial equity. Our aim is hence to investigate the spatial patterns of urban GI and disclose how spatial patterns affect spatial equity of GI in typical residential areas. The sample sites are in a central European city, Leipzig, the fastest growing city in Germany at present, with high pressure on urban growth. To elaborate an innovative approach, this study draws up a cascade of three methodological stages: 1) deploy the approach of an urban Morphological Spatial Pattern Analysis (MSPA) to compare urban GI patterns in three typical residential local districts, 2) use the GI-adapted Gini coefficient to measure spatial equity of GI distributions, and 3) explore the relationships between GI spatial patterns and spatial equity of GI for each residential type. In the context of three typical residential areas in Leipzig (i.e. (semi-)detached houses, linear multistorey housing estates, and perimeter blocks), a combination of the MSPA and a spatial equity measurement assists our novel exploration to disclose the relationships between the spatial patterns and the equity of GI distributions. Thus, we can prove strong similarities on the characteristics of spatial patterns in each residential type and observe a tendency of increasing equity from (semi-)detached houses to linear housing and further to perimeter blocks. As significant findings for the support of strategic urban GI planning, we discover that GI cores provide a restricted increase of spatial equity that limited to the lack of space. Furthermore, we suggest more GI bridges to enhance structural connectivity as well as spatial equity. This paper depicts the spatial equity of GI distributions in typical residential areas from morphological perspective, and thus further underpins urban GI planning for strategic networks as a key principle of the urban GI concept.

1. Introduction

Rapid urbanization has motivated the development of urban Green Infrastructure (GI) as a planning strategy to support the well-being of urban dwellers (Coutts and Hahn, 2015; Tzoulas et al., 2007). Urban GI has evolved since its inception in the mid-1990s (Firehock, 2010; Pauleit et al., 2011) and has been defined as the strategically planned and managed networks of natural and semi-natural lands, features and green spaces, and terrestrial, freshwater, coastal and marine areas in urban areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and provides associated benefits to human populations (Benedict and McMahon, 2006; European Commission (EC), 2012, 2016; Naumann et al., 2011). As for the man-made infrastructure, which is also known as “gray infrastructure”, has been described as the functional support system of urbanized areas

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(Wang and Banzhaf, 2018). Urban GI planning can be defined as "a strategic planning approach that aims at developing networks of green and blue spaces in urban areas that are designed and managed to deliver a wide range of ecosystem services" (EC, 2013; Maes et al., 2019). Planning for the connectivity and multifunctionality of urban green and blue spaces are inherent principles in this definition (Pauleit et al., 2018). Moreover, it has been suggested that urban GI should strive to integrate green with gray infrastructures, e.g. for sustainable storm water management, and be developed in a socially inclusive process to involve all relevant stakeholders. This has spurred an agreement that urban ecology (Marcus and Colding, 2014; Samuelsson et al., 2018), as a lens (Colding and Barthel, 2017), must be used to reflect and highlight the multiple ecosystem services (ESS) (Samuelsson et al., 2019) provided by urban GI. Among the multiple objectives GI has (EC, 2013) are the promotion of biodiversity, climate change adaptation, the provision of recreational spaces for citizens and supporting the shift towards a green economy (Pauleit et al., 2018).

Urban GI planning should also strive to achieve a relatively equal socio-ecological development (Pincetl and Gearin, 2013) by balancing disparities in the distribution of GI (Kabisch and Haase, 2014) and its ESS. Spatial equity of GI distributions is crucial for individual urban inhabitants for having the same distance to access services (Heckert and Rosan, 2016). It implies that spatial analyses on the distance of citizens to urban GI, such as at cognitive level, where people in the street experience urban green spaces (Colding and Barthel, 2017; Marcus and Colding, 2014), and at eye level (Samuelsson et al., 2019) or at site level (Rall et al., 2019) where urban dwellers may participate into the strategic planning, may shed new light on the connectivity (Samuelsson et al., 2019) and configuration of urban GI. Allocation of GI is influenced by the character of gray infrastructure, namely amount, density and configuration of the built-up structures (Marcus and Colding, 2014), roads, and any other paved surfaces (Wang and Banzhaf, 2018). Therefore, the spatial distribution and the character of different urban morphology types such as residential areas, commercial and industrial zones (Gill et al., 2008; Pauleit and Duhme, 2000), determine the quantity and quality of urban GI (Romero et al., 2012; Van der Zanden et al., 2013). Consequently, urban GI planning will benefit from the analysis of the spatial patterns of GI to reveal the intertwined relationships between GI and built-up structures (Pauleit and Duhme, 2000; Wickop et al., 1998). However, studies concentrating on the spatial patterns of urban GI are still rare (Alberti and Marzluff, 2004; Holt et al., 2015), especially in residential areas, even though they are meaningful for urban GI planning.

Evidence has emerged to support the claim that spatial patterns of built-up structures are influencing the ecological functional connectivity (Saura et al., 2011; Vogt et al., 2007, 2009; Wickham et al., 2010) and thereby the provision and functioning of GI (Alberti, 2005; Bierwagen, 2005; Cavan et al., 2014; Tratalos et al., 2007; Whitford et al., 2001). It necessitates more and in-depth studies concerning spatial patterns and their effects on biodiversity and urban ESS (Alberti, 2005). The supply of urban ESS, as Samuelsson et al. claimed (2018; 2019), is influenced by the urban form as well as the spatial patterns of urban areas. To describe the spatial patterns, various methods and tools have been developed and applied in urban ecology (e.g., McGarigal and Marks (1995); Kim and Pauleit (2007); Kuttner et al. (2013)) to reveal the links between urban GI patterns with ecological and social functions (Luck and Wu, 2002). They comprise methods such as Fragstats (Luck and Wu, 2002; McGarigal et al., 2002; McGarigal and Marks, 1995), which provides a series of landscape metrics (e.g. area/density, patch shape index and proximity metrics) to detect the urbanization gradient of landscape patterns (Kupfer, 2012; Luck and Wu, 2002) and biodiversity conservation (Kim and Pauleit, 2007), and tools like least cost measures (Sutcliffe et al., 2003) as well as genetic patterns that offer a more ecologically oriented approach to quantifying spatial patterns (e.g., Chardon et al. (2003); Coulon et al. (2004); Hokit et al. (2010)). Other graph-based approaches are also applied, for instance, the Conefor Sensinode tool (Saura and Torne, 2009) quantifying habitat patches for connectivity by calculating nodes, links, and graph-based metrics, including the number of links, number of components, integral index of connectivity and so forth; or the Circuitscape tool (McRae and Shah, 2009) which could calculate and map measures of resistance, conductance, current flows, and voltage. These approaches are widely utilized to analyze the structural landscape metrics and connectivity, but they are all rooted in graph, network, and circuit theory (Kupfer, 2012), and being limited by inconsistent evaluation results from human interpretation (Ostapowicz et al., 2008). Their definitions of thresholds such as patch width are in terms of selected contexts. With regard to methods that analyze spatial patterns, the former (i.e. structural indices of patch shape such as perimeter to area ratio) and the latter (i.e. graph-based approaches) can explore the importance of corridors as connectors between nodes (Ostapowicz et al., 2008) in a network, but only after these corridors have been defined elsewhere.

The Morphological Spatial Pattern Analysis (MSPA) approach developed by Vogt et al. (2006) and Soille and Vogt (2009) has been an evolution apart from the aforementioned methods, because it can map corridors as structural links between core patches and this feature cannot be achieved with any other methodologies (Kupfer, 2012) (i.e. neither landscape metrics (structural indices) nor graph-based approaches). Indeed, MSPA is a mathematical morphological algorithm that performs a segmentation analysis of the foreground objects against the background matrix (ibid.) as well as a tool to describe spatial patterns and connectivity of urban GI (Ramos-Gonzalez, 2014). MSPA makes pattern analyses more interpretable by incorporating visualization maps, classifying and mapping individual pixels into different categories, such as core, bridge, loop, branch, perforation and edge (Barbati et al., 2013). Therefore, the MSPA offers an effective approach to investigate GI in heterogeneous urban areas, allowing to identify and quantify the spatial patterns of GI (Nielsen et al., 2016) and distinguish between them (e.g. bridges as connectivity for species dispersal and movement) (Barbati et al., 2013). Up to date, MSPA approach has been used primarily in forest areas (Goetz et al., 2009; Riitters, 2011) to detect forest connectors (Saura et al., 2011), monitor forest composition and configuration (Ostapowicz et al., 2008) in ecological restoration areas for site prioritization (Wickham et al., 2017), or in riparian zones to identify the structural riparian corridors for conservation and management purposes (Clerici and Vogt, 2013). However, there are few studies that have been performed in urban areas (Ramos-Gonzalez, 2014), and in this paper the MSPA is applied in the residential areas for the very first time.

In this study, we aim to use the MSPA approach to shed light on the relationships between the distribution and the connectivity of urban GI and built-up structures in typical residential areas of a central European city for the analysis of spatial equity and functionality of urban GI. It is hypothesized that residential areas show diverging morphological spatial patterns of GI and simultaneously result in uneven GI distributions and connectivity (e.g. species dispersal and movement). Aside from exploring urban GI spatial patterns for equity in typical residential areas, our specific objectives are: 1) to compare urban GI morphological spatial patterns in different types of residential areas, 2) to analyze spatial equity of GI using GI-adapted Gini coefficient, 3) to investigate the relationships between GI's spatial patterns and Gini coefficient in distinct residential types.

2. Methodology

2.1. City of Leipzig, Germany, and its sample sites

Our study deals with the city of Leipzig, Germany. Leipzig is located in the north-western part of Saxony and covers an area of 297 km^2 (Fig. 1). With 596,517 inhabitants in 2018, it is the largest city in Saxony with a population density of 2008 inhabitants per km^2. One of the most well-preserved alluvial forests in Europe traverses Leipzig. From south to north and then towards the northwest, the forest stretches through the urbanized area, serving as the green lung of the city. This is one of the main reasons why it is one of Germany's greenest cities with an average of 254 m^2 vegetation cover per inhabitant (Maes et al., 2019; Stadt Leipzig, 2003, 2018). Another notable phenomenon of GI is the high share of public community garden allotments (approx. 1240 ha) (Stadt Leipzig, 2018) which provides additional recreational space for thousands of residents and has a positive influence on the local climate (Cabral et al., 2017).

During the last decade Leipzig has become the fastest growing city in Germany with considerable increase in economy and cultural diversity. Moreover, Leipzig prides itself with its eagerness in sustainable urban development (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), 2007; Stadt

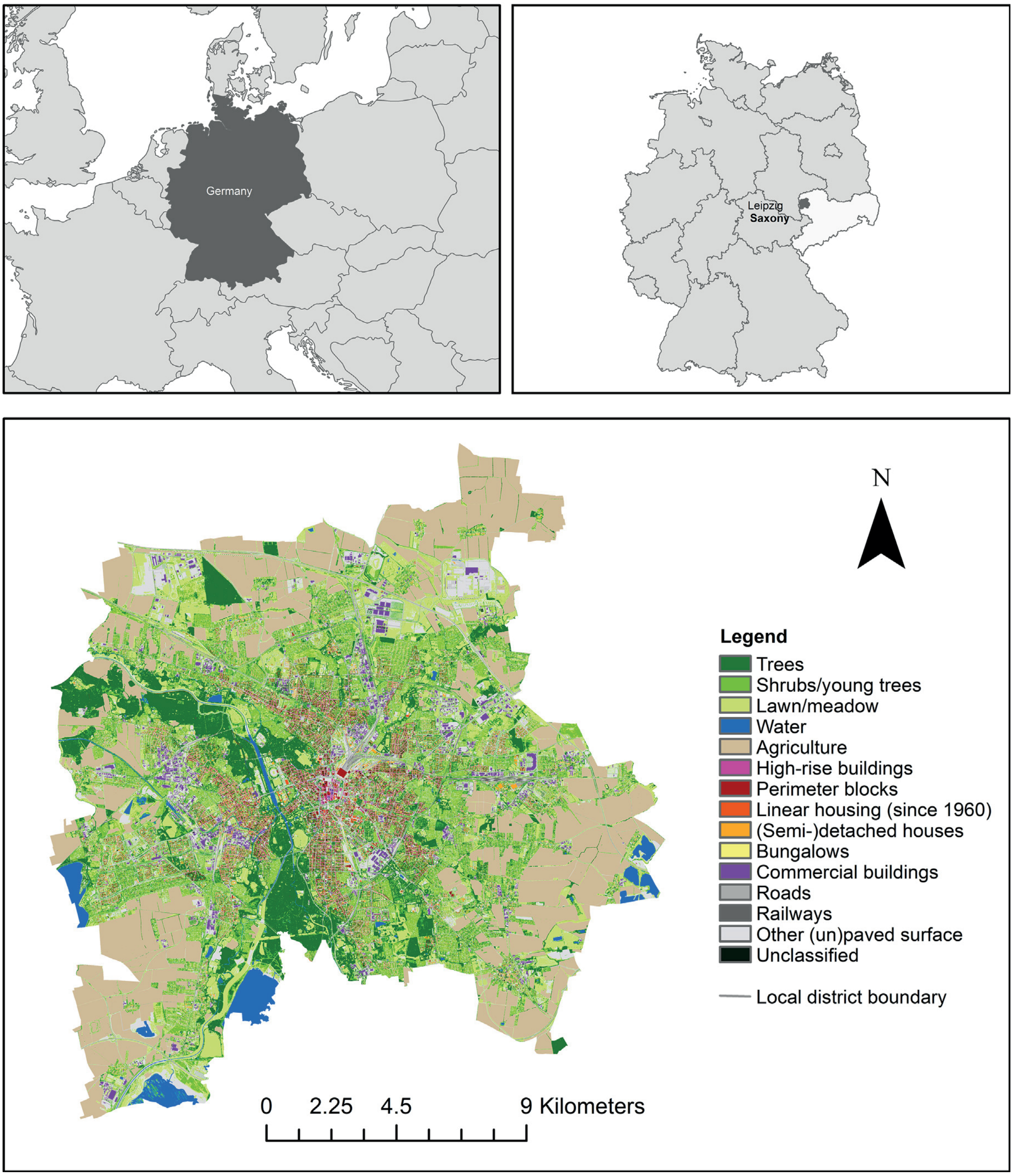


Fig. 1. Location of the case study: (a) Germany in Europe, (b) Leipzig in Germany, (c) The City of Leipzig, 2012.

Leipzig, 2019). As part of these efforts, urban planning makes major endeavors in re-densifying the municipal space thereby preventing urban sprawl. As a consequence, land development processes have been leading to a competition between GI and housing including public infrastructure (Fig. 1). Grounded on a high recognition for maintaining or even enhancing urban ecosystems and their services by fostering local GI, the city council has developed a GI quality concept, the so-called Masterplan Green Leipzig (2030) (Stadt Leipzig, 2018). Nonetheless, the increasing population numbers and density provoke high leverage. The need for providing schools, kindergartens, local amenities and new dwellings for residents is a strong driver shaping the character of urban compaction. Maintaining a green city that secures a high environmental quality of urban life and offering housing and public infrastructure are currently the major challenges for urban planning. At present, the creation of a new urban development concept for Leipzig is on its way (Integrated urban development concept (INSEK) Leipzig 2030; Stadt Leipzig, 2018) where information such as the one generated in this study is needed.

The structure of the built-up area in Leipzig is characterized by three major types of residential buildings (Fig. 2): perimeter blocks (Wilhelminian-style buildings) with 5—6 storey high buildings in a block alignment with an interior courtyard, linear multistorey housing (mainly prefabricated slab buildings) of mostly 6-16 storey high buildings with common spaces in-between, and 1-2 storey, (semi-)detached houses (single and duplex houses) with gardens. Being a fairly homogeneous city (Figs. 2 and 3), many of the 63 local districts can be assigned to one of these dominant types. The city has one of the highest proportion of Wilhelminian-style residential buildings (Gründerzeitbebauung) in Germany. The construction of these buildings began during the reign of King Wilhelm II after 1850 and continued until 1914. Much later, during the era of the German Democratic Republic, one of the country's largest prefabricated slab building complexes were built in Leipzig. They became home to more than 80,000 residents in the 1980s (Banzhaf et al., 2018). The construction of single and semi-detached (or duplex) family houses started in the 20th century in large designated settlement areas and is continued up to date, albeit rather patchy and dispersed throughout the city.

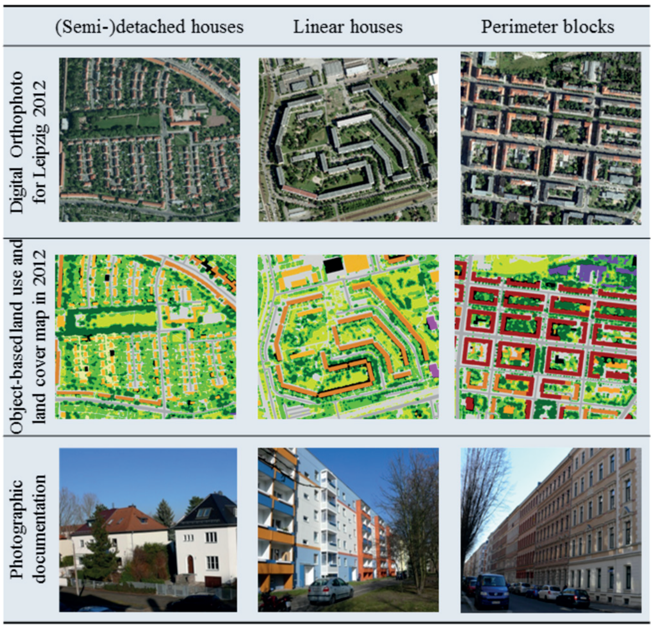


Fig. 2. Digital orthophotos (DOP) (2012), corresponding object-based land use and land cover map, and photographic documentation for each of the dominant urban structure types. Sources: DOP by Ordnance Survey, state of Saxony, Germany; map own calculations, photography by E. Banzhaf.

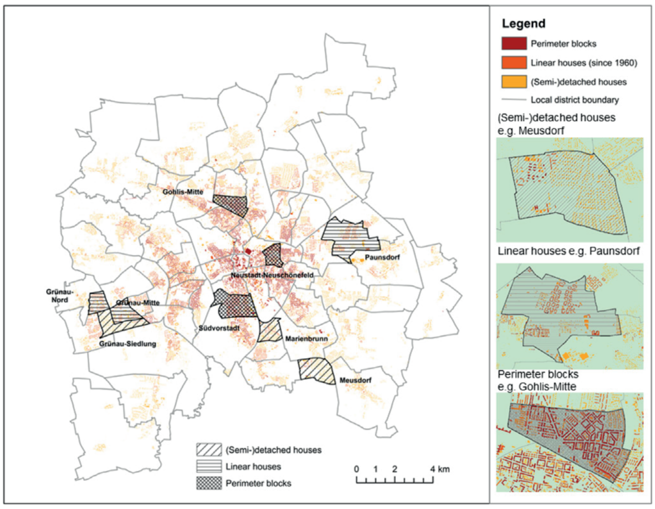


Fig. 3. Location of the nine sample sites especially highlighted in the City of Leipzig with its 63 local districts.

We applied and tested our method for selected sample districts (Fig. 3) considered as fairly representative for the three residential types. For an even urban coverage, we selected three sample districts each: typical local districts for the Wilhelminian-style perimeter blocks are Gohlis-Mitte in the north, Neustadt-Neuschönefeld in the central east, and Südvorstadt in the south, constructed during the first period of spatial expansion (mainly around the turn of the 19th century). Linear multistorey housing estates are rather large and located towards the fringe of the urban area. As Grünau was one of the largest linear housing estates in the former German Democratic Republic (GDR), being constructed in the 1970s and 1980s; thus, we chose two local districts from this vast area in the southwestern part of the city (i.e. Grünau Mitte and Grünau Nord), and Paunsdorf as the third sample district in the eastern part. With respect to the typical urban structure of (semi-)detached houses we decided to exclude the most recent areas under development due to patchiness and present lack of GI. Instead, we chose three residential areas Grünau-Siedlung in the west, Marienbrunn in the central south and Meusdorf at the southeastern outskirts of Leipzig that were built between the 1920s and 1930s. All the selected nine districts have a stable and long history of developments for which their respective municipal boundaries are stable before/after German reunification (Kabisch et al., 2018). Our selection did not include the local districts that were incorporated into the City of Leipzig between 1993 and 2000 as a municipal area reform, concerning they have a more rural character. The principles of our selection are, in essence, the historical urban developments (Kabisch et al., 2018), the fairly representative (Banzhaf et al., 2018), and the high population densities for the year 2012 in the City of Leipzig (Stadt Leipzig, 2012), for the purpose of underpinning our aim of exploring the green spaces mostly used.

2.2. Data collection — spatial data and materials

To gain spatial information on the urban land use and land cover, we employed digital orthophotos (DOP), a digital elevation model (DEM) and a digital surface model (DSM) at very high resolution. These datasets were processed in an object-based image analysis (OBIA) approach described by Banzhaf et al. (2018), in which different datasets were all rescaled to 1 m ground resolution for the year 2012. The advantage of this dataset is not only its scale but also its three-dimensional classification scheme and refined categories. The categories comprise urban built and green structures including green cover types such as trees, shrubs/young trees, lawn/meadow, agriculture and water giving information on the typical residential areas explained in a previous study (Banzhaf et al., 2018). Therefore, the object-based classification facilitates our research from two aspects: first, to analyze the morphological patterns of GI at a very high spatial resolution, and second, to extract typical residential areas for the analysis of GI towards equity and connectivity. In terms of statistical records on demographic data, we included all urban populations with first and second places of residency living in Leipzig. By also considering those with a second residency we paid tribute to international students, commuters, and those who contribute to a realistic picture of the urban dwellers and who use GI.

2.3. Spatial pattern analysis method

The morphological spatial pattern analysis (MSPA) was first introduced by Matheron et al. in 1967 (Matheron, 1967) and then enhanced by Soille (2013). It has been further applied in landscape ecology in depth by Vogt et al. since 2006 (Soille and Vogt, 2009; Vogt and Riitters, 2017; Vogt et al., 2007). This approach has so far been applied to classify spatial patterns, as well as to map functional networks (Vogt et al., 2009; Wickham et al., 2010) and landscape corridors (Clerici and Vogt, 2013; Vogt et al., 2007). Since then, the MSPA has continued to be developed for landscape ecological studies. In this paper we used the latest GuidosToolbox 2.8 to conduct our GI morphological mapping. This toolbox was recently updated by the Joint Research Centre of the European Commission. Preprocessing steps comprised the reclassification of spatial data into a binary map using ArcGIS 10.6 compared to Soille and Vogt (2009) and Wickham et al. (2017), which included GI and built-up structures to match our research focus, namely the spatial patterns of GI.

In order to explore urban GI patterns applying MSPA (Vogt and Riitters, 2017), we defined the primary green cover types (Davies et al., 2015) that are available from our spatial data source as our foreground (primary targets) map, and simultaneously set other built-up structures as our background map. From the classified dataset we selected trees, shrubs/young trees, lawn/meadow, agriculture, and water as our five focal classes for the mapping of the GI morphological patterns, setting all other built-up structures, including railways, paved surfaces, commercial buildings etc., to the background. These GI categories reflect all primary GI types in the City of Leipzig providing ESS in urban areas. When carrying out the spatial pattern analysis we were in line with the methodology by Wickham et al. (2010). Although a ready-made MSPA toolbox was available, we decided to customize ours according to our sophisticated research focus and our much more refined input data. For this reason we undertook preprocessing steps like tiling to have all data tailored for further processing. Preprocessing comprised i) cutting buffered sub-tiles, ii) processing buffered sub-tiles for MSPA, and iii) resampling the final image to comply with the prerequisites for our MSPA investigation and at the same time support our aim to keep our high resolution dataset at the spatial resolution of 1 m; otherwise there are potential risks of losing information due to the change of spatial resolution, because without aforementioned preprocessing, our input data are restricted to a square map of 10000 * 10000 pixels for the MSPA processing (Vogt and Riitters, 2017). As the second step, we set the connectivity as eight-neighbor to analyze each pixel being surrounded by different pixels in eight directions.

According to our customized method in Section 2.3, our adapted MSPA resulted in seven classes of GI spatial patterns. They are named core, bridge, loop, branch, edge, perforation and islet. These classes reflect the spatial heterogeneity of GI in the residential areas. Instead of overlying several maps in geographic information system software, our method from Soille and Vogt (2009) was based on concepts from mathematical morphology (Soille, 2003). The MSPA classes are defined in Table 1.

2.4. Data processing for the calculation of the GI-adapted Gini coefficient

Traditionally, Gini coefficient has been employed in economics as a valid index to measure the income inequality of inhabitants. However, a growing number of references (Kabisch and Haase, 2014; Li et al., 2017; Wüstemann et al., 2017; Xu et al., 2018) more recently demonstrate that it can be expanded to an effective index to assess sustainable urban development as well as the provision of cultural ecosystem services (Kabisch and Haase, 2014; Li et al., 2009). In these cases, the supply of the nearby GI is regarded to be more beneficial for residents in terms of daily short-term recreational services (Xu et al., 2018), for which the maximum distance from the residence locations to nearby GI should not be further than 300 m (Kabisch et al., 2016; Lauf et al., 2014), and the minimum size of GI patch should cover approximately 2 ha (Handley et al., 2003; Lauf et al., 2014).

A newly adapted index will foster our analysis to point to environmental equity in a spatially explicit way (i.e. the GI-adapted Gini coefficient). We used this index, which is expressed as follows, to measure the spatial equity of the GI distribution in local districts with different dominant residential types.

$$G = 1 - \sum_{i=1}^{n} \frac{P_i}{P} (B_{i-1} + B_i) \tag{1}$$

where P is the total population of the local district; P_i is the population number of the grid cell i; and B is the cumulative share of GI

Table 1
Classification of the morphological spatial patterns.

MSPA classes	Definitions
Core	GI surrounded by all sides (8-connectivity) by GI and greater than 3 m distance from built-up areas
Bridge	GI that connects two or more disjunctive areas of GI cores
Loop	GI that connects an area of GI core to itself
Branch	GI that extends from one area of core, but does not connect to another area of core
Perforation	Transition zone between the GI and built-up areas for the interior regions of GI, and has the shape of a doughnut in which a group of GI types is shaped by the perforations (inner edges).
Edge	Transition zone between GI and built-up areas
Islet	Unconnected class without core.

in a 300 m buffer around grid cell *i*. The GI-adapted Gini coefficient ranges from 0 to 1, with 0 representing total equity, and 1 indicating absolute inequity.

The GI-adapted Gini coefficient was calculated according to the following steps: first, GI patches were selected with a minimum size of 2 ha, and the population density for the residential areas in each local district was computed, dividing the population number of the respective local district by the total residential areas within the boundary of the local district; second, each sample local district was intersected with a 100 m × 100 m grid file in ArcGIS 10.6, and the grids with their centroids located in each sample district were collected; third, for each sample local district, the population number within each grid cell and the area of GI (selected in the first step) within a 300 m buffer around the centroid of the grid cell were calculated. Grid cells with less than two residents were omitted from further mathematical processes, and the GI-adapted Gini coefficient was quantified for all sample local districts.

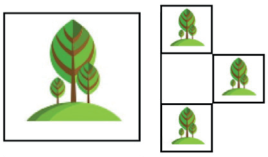
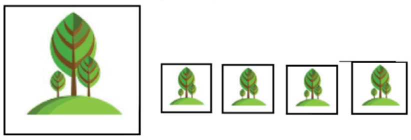
3. Results

3.1. Morphological spatial pattern analysis for typical residential areas

3.1.1. Delineation and interpretation of morphological spatial patterns

Our developed MSPA resulted in seven classes with specific geometric features. This prerequisite enabled us to define and analyze our classes in depth according to our research aim and the underlying Land Use and Land Cover (LULC) classes to understand the structural connectivity of GI. As one significant result, we characterized each class in Table 1 as different GI patterns in terms of the GI concept by Wang and Banzhaf (2018), through which we were able to better understand their relationships in our local sample districts. As Table 2 shows, MSPA classes may either belong to *GI exclusively* (pure GI patterns) or they may be part of the *GI*

Table 2
Conversion of the MSPA classes into structure classes

MSPA classes	Structure classes	Illustrations
GI exclusively		
GI core	GI core	
GI bridge	External connectivity 1: GI core areas to other different GI core areas	
GI loop	Internal connectivity 1: GI core areas to the same GI core	
GI branch	Partial (half) connectivity	
GI connected to built-up areas		
GI perforation	Internal connectivity 2: transition zone between GI to built-up areas for interior regions of GI cores.	
GI edge	External connectivity 2: transition zone between GI and built-up areas.	
GI islet	Unconnected	

connected to built-up areas. The *GI exclusively* classes encompass GI core, bridge, loop and branch. As for the *GI connected to built-up areas*, they enclose GI perforation, edge and islet. They all contribute to structural connectivity at different extents.

The GI core in Table 2 is usually composed of a broad spectrum of types of green and GI elements, encompassing the currently primary functioning GI. Other GI spatial patterns such as bridge, loop, and branch, however, are classified in terms of their relationships with surrounding GI core. As one significant result, we converse MSPA classes into seven different structural classes and they reflect different intensities of structural connectivity (Table 2). GI bridges (Fig. 4) that connect to the different GI cores are significant corridors for providing favorable habitat and paths from one core to another. GI loops represent shortcuts connecting spaces of a core area to itself. In general, both the bridges and loops indicate functional pathways, in which maintenance is crucial to sustain any transfer of individuals between the same or different GI cores. Branches might be developed from bridges and loops, and further recognitions of locations of branches and bridges would then provide notices where there might be vulnerable GI corridors. Perforations and edges are both transition zones between GI cores and the built-up area.

3.1.2. Comparison of the GI morphological spatial patterns in different types of residential areas

The GI spatial patterns of all sample local districts were extracted and the results for our nine samples are illustrated in Fig. 5. Each of the three local districts dominated by (semi-)detached houses has similar structures/distributions of morphological spatial patterns. From high to low, the orders of proportions of the top five spatial patterns are the same in proportions (i.e. GI core > GI bridge > GI edge > GI loop > GI branch). There are relatively high fractions of GI core areas at all of the three cases, i.e. Grünau-Siedlung, Marienbrunn, and Meusdorf, which reflect a relatively high level of pure GI coverage. With respect to the GI bridges and GI edges, these two patterns accounted for almost the same percentage. As a result, the probabilities between external connectivity 1 (GI core areas connected to another different GI core area) and external connectivity 2 (GI cores to built-up areas) were nearly the same. The respective proportions of the overall spatial patterns were quite similar from GI core to islet.

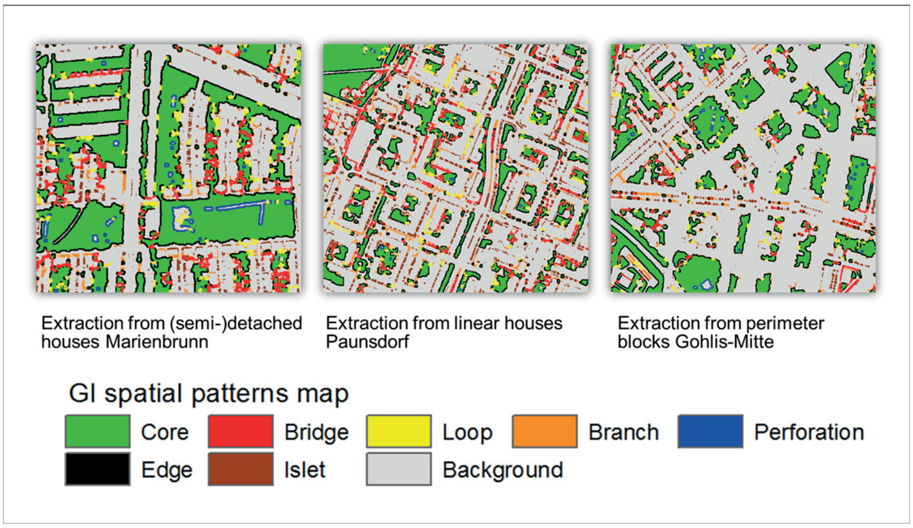
As for the local districts prevailing linear multistorey housing estates, it shows similarities in the distributions of GI morphological patterns as well. From high to low, the orders of proportions of the first five spatial patterns are consistent, i.e. GI core > GI edge > GI bridge > GI branch > GI loop. For this residential type, it is interesting to note that the proportions of GI bridge are almost half of the GI edge patterns connected to the other built-up areas. This result explains that GI in districts dominated by linear multistorey housing frequently reaches right up to typical building structures rather than to other GI cores. It reveals potential limits of GI connectivity in these sample districts for the reason that GI edges (external connectivity 2) have less structural connectivity compared to GI bridges (external connectivity 1) according to Table 2.

At those local districts dominated by perimeter blocks which contain mostly Wilhelminian-style buildings, i.e. the typical residential districts of Gohlis-Mitte, Neustadt-Neuschönefeld, and Südvorstadt, it is notable that the fractions of GI cores and GI islets are the highest compared to the aforementioned two sample districts. However, compared to the districts dominated by linear multistorey housing types, the GI bridges are apparently much less than half of GI edge patterns. During that era of urban expansion, an extremely high pressure was put on urban dwellings because of the strong growth of cities undergoing industrialization (mainly second part of the 19th century). Therefore, two contrasting urban structures were created in those days that still predominant the urban character of Leipzig (i.e. Wilhelminian-style perimeter blocks in the block alignment (some of them with interior yards), but hardly any GI in streets, and few large areas with allotment gardens that met the dwellers' need for green space).

As one significant MSPA result, each of the three typical residential areas has its own spatial GI patterns, while within the same type of residential districts, the GI patterns are similar. The section that follows will explore how these characteristic patterns influence the equity of GI in residential areas.

3.2. GI-adapted Gini coefficient

To know the spatial equity of GI distributions, we chose the GI-adapted Gini coefficient index. In our nine sample local districts (Fig. 6), the Gini coefficient ranges from 0.096 to 0.463, representing large differences of GI distributions from even to comparatively uneven, given that the smaller Gini coefficient indicates a


Extraction from (semi-)detached houses Marienbrunn

Extraction from linear houses Paunsdorf

Extraction from perimeter blocks Gohlis-Mitte

Fig. 4. Extractions from GI spatial patterns map in three types of residential areas.

higher equity of potential access to the same amount of GI and vice versa.

The overall Gini coefficient of each exemplified residential district was evaluated as well. As dash lines in Fig. 6 show, the spatial equity of GI distributions varies with reference to the existing type of residential areas. Despite the small variations of the Gini coefficient among different local districts, there is an apparent tendency that the GI coefficient strikingly increases from samples with (semi-)detached houses to linear multistorey housing districts, and shows the highest rates at local districts with perimeter blocks. It means that GI distributions in the districts predominated by perimeter blocks are the most unequal, while those local districts with (semi-)detached houses show the most equal distribution of GI.

Compared to those local districts dominated by linear multistorey housing and perimeter blocks, the GI distributions of the local districts with (semi-)detached houses are relatively even. More strikingly, GI availability is most uneven in local districts with perimeter blocks, even though there are interior courtyards in some blocks of these historical building complexes. Consequently, the residents in such typical residential districts (e.g. Neustadt-Neuschönefeld, Gohlis-Mitte, or Südvorstadt) probably have the lowest equity to accessing the same amount of GI. Evidently, those local districts with prevailing (semi-)detached houses have a higher spatial equity of GI distributions. Beyond, their residents can much easily access the nearby GI for further recreation.

3.3. Relationships between GI spatial patterns and Gini coefficient in the residential types

The spatial patterns of each type are different (Fig. 7), even though the GI core accounts for the biggest fractions among all the three different structural areas. As a significant result, we observed positive correlations between GI bridge and edge patterns with the spatial equity of GI distributions in (semi-)detached housing areas. In these areas a large number of GI bridges and edges connect to other GI cores and sealed surfaces respectively, and the GI distributions usually show more equity in these predominant local districts.

For the same type of building structures, the spatial patterns of GI are rather similar as Figs. 5 and 7 show. For instance, the proportions of both bridge and edge for the local districts dominated by (semi-)detached houses are quite similar. Therefore, the GI cores are relatively well connected, while the findings also imply potential vulnerability of GI because the edge is usually a transition zone between GI and built-up areas. The differences in the proportion of edge and bridge areas in (semi-)detached dominated local districts are small, whereas those in the local districts dominated by linear multistorey housing and perimeter blocks are larger. Particularly for the latter, the results suggest a limited connectivity between GI core areas. Overall, it appears that GI cores alone cannot firmly ascertain a high level of spatial equity as the Gini coefficients indicate.

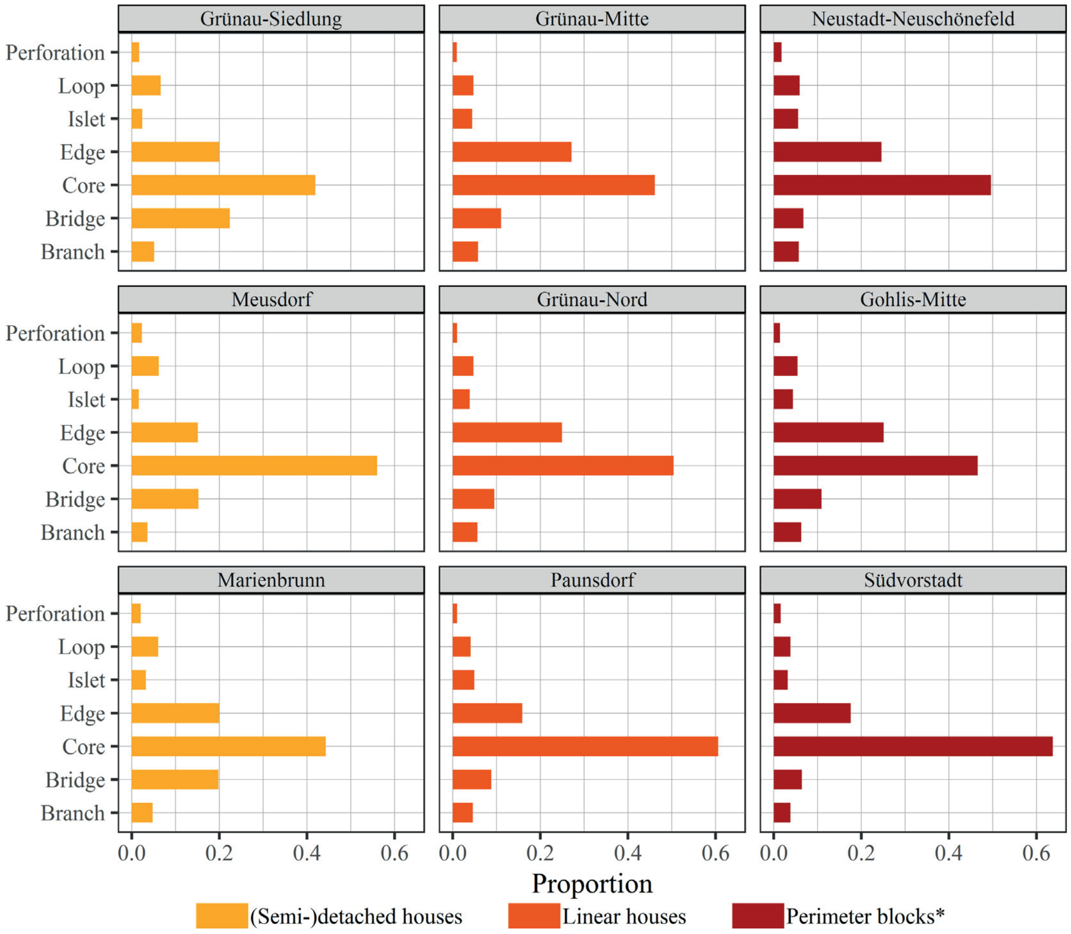


Fig. 5. MSPA of nine local districts, three dominated each by (semi-)detached houses, linear multistorey housing and perimeter blocks respectively (* mostly Wilhelminian-style buildings from 1850 to 1914).

4. Discussion

We analyzed the spatial patterns in the local districts representing the three dominant types of residential areas in Leipzig, Germany. The typical urban structure comprises (semi-)detached houses, linear multistorey housing estates and perimeter blocks. In this paper, the underlying hypothesis — local districts with respective predominant residential structure types that underlie diverging morphological spatial patterns of GI, and which may result in uneven GI equity — is attributed to the combination of morphological spatial pattern analysis with an index that measures spatial equity to verify this assumption.

Our analysis provides a classification of seven GI feature classes (Table 1) and different structure classes (Table 2), covering multiple aspects of the GI spatial patterns of our sampled local districts and their structural connectivity. It enables us to discuss how these urban GI patterns affect the ecosystem functions respectively. GI cores containing GI types such as trees, shrubs/young trees, lawn/meadow, agriculture, and water can be significant habitats for species (Wickham et al., 2010) and represent the major ESS provisioning areas (Riitters, 2011). In our sample local districts, they are particularly important since they affect species habitat and resource availability. The core contains shrubs/trees that provide regulation services, e.g. cooling capacity (Goetz et al., 2009), lawn/meadow for recreational cultural services, for insect pollinator activities and movement paths (Vogt et al., 2007), agricultural areas serve for food provision services in urban areas and so forth. The bridge class characterizes the potential movement pathways (ibid.), not only for the native plant and animal species but also for residents. These spatial patterns are witnessed in our nine local test districts with a large number of urban dwellers. Bridges may be the vulnerable GI for future fragmentation and conversion to any built-up structures. Furthermore, they are primary networks for GI connectivity (Ahern, 2007, 2011) because they join two or more disjunctive areas of GI cores, such as stepping stones, which might be the primary movement paths for insects. Both loop and branch classes are connected to GI core. As for the perforation and edge, they are transition zones between GI and built-up structures. It seems that perforations are the inner edges and thus indicate higher structural connectivity to GI core. It is the very nature of an islet to be disjoint and usually too small to contain a core. Islets might be a small number of trees, shrubs/young trees surrounding any built-up structures like buildings and parking lots, or along streets, not large enough to be recognized as GI core areas, even though they reflect small and fragmented GI connected to any sealed surfaces. Native flora and fauna in isolated patterns such as islets usually decline as a result of habitat loss and interspecific interactions (Alberti and Marzluff, 2004), reduced connectivity (Alberti, 2005), and then a loss of biodiversity (Goetz et al., 2009; Wickham et al., 2017).

In comparing urban GI morphological spatial patterns in different types of residential areas, we discover that the single spatial pattern of GI in local districts with the same residential building structure show their own diverse configurations. However, a general tendency of similar distributions of morphological spatial patterns is observed for each type of residential areas, respectively

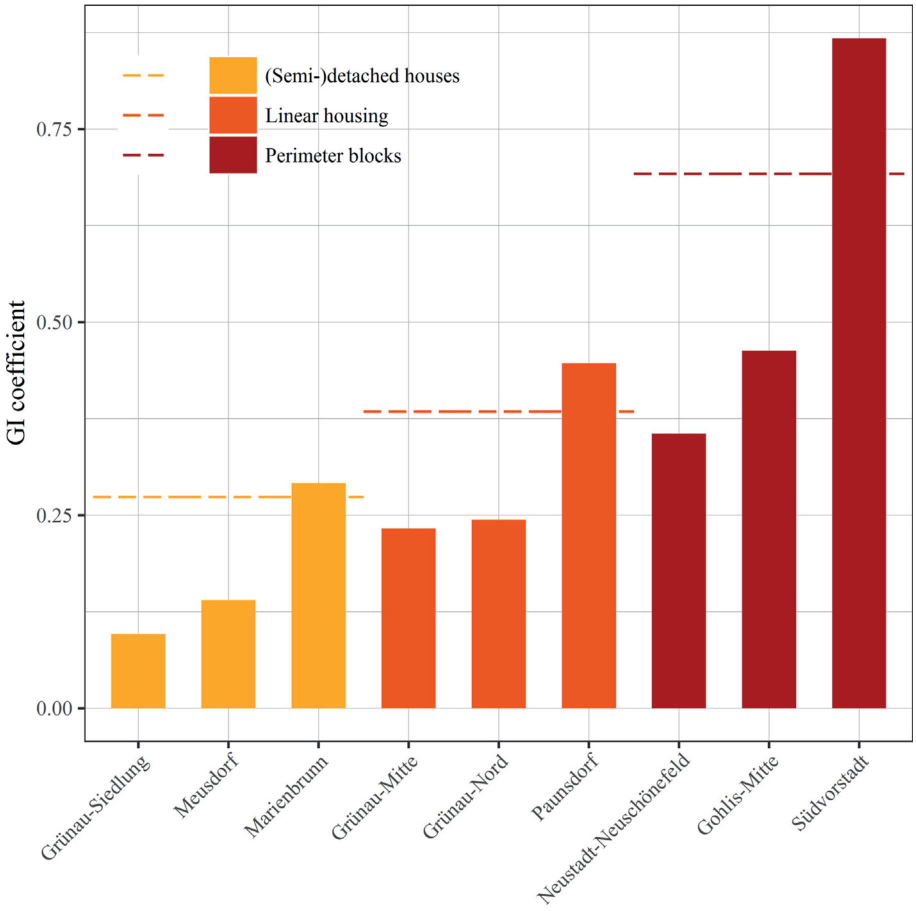


Fig. 6. The Gini coefficient of the nine sample local districts dominated by (semi-)detached houses (left), linear housing estates (center) and perimeter blocks (right); dash lines illustrate the Gini coefficient for each type of residential areas.

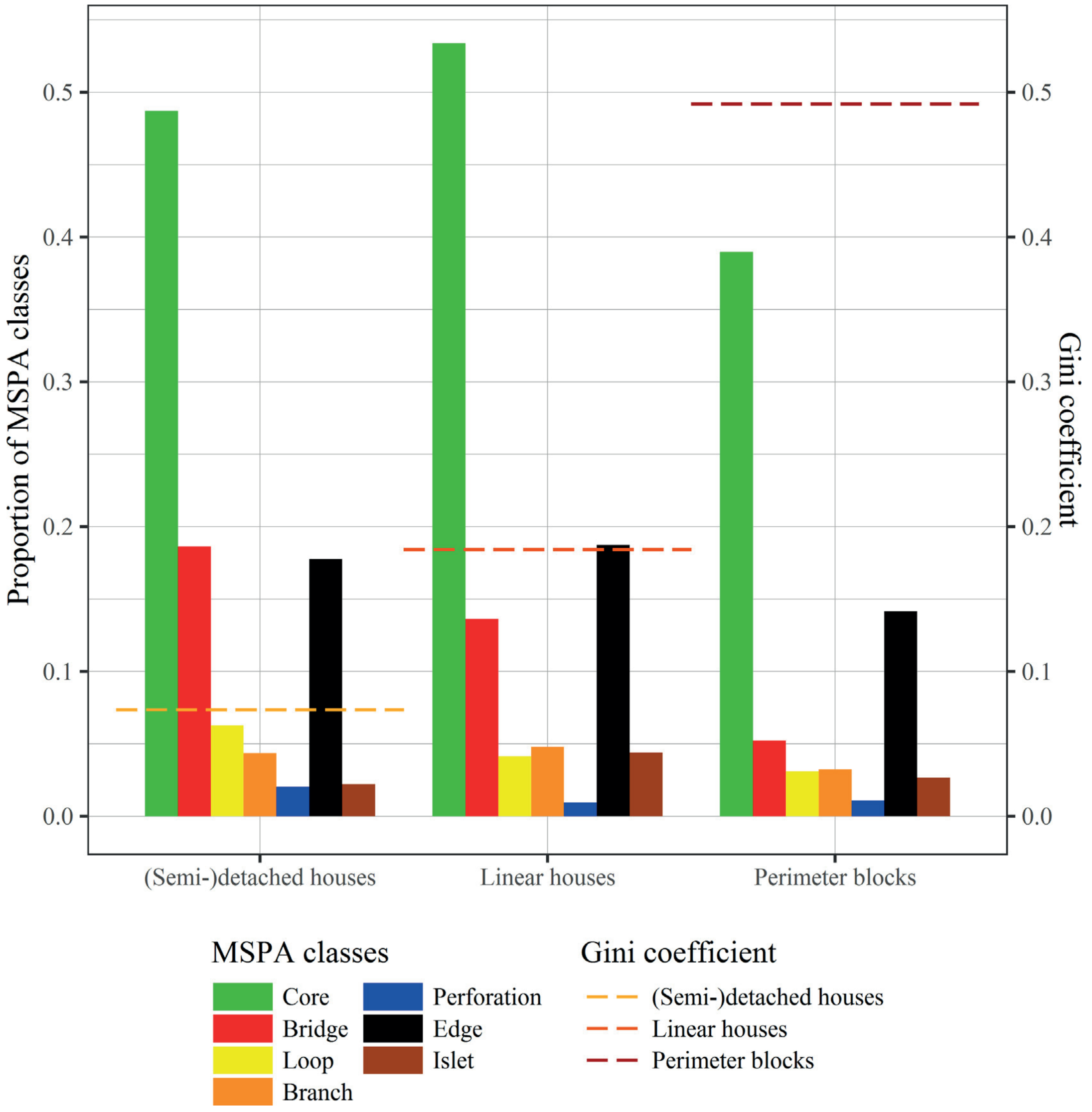


Fig. 7. GI-adapted Gini coefficient for three types of typical residential areas which are dominated by (semi-)detached houses, linear houses and perimeter blocks respectively; colors are in line with the general color scheme using MSPA).

predominated by (semi-)detached houses, linear multistorey houses and Wilhelminian-style perimeter blocks. In other words, all local districts where (semi-)detached houses are prevailing show almost the same proportions of GI feature class bridge and edge; as for local districts predominated by linear multistorey and perimeter blocks, their GI bridges decrease to less than half compared to the fractions of GI edges. Besides, when referring to the feature class loop, it represents a shortcut by directly connecting core areas. In our study, bridges made positive effects on the structural connectivity of GI, but their implications for the corresponding spatial equity of the GI distributions are still unclear. At present, we are not yet able to advise whether or not more loops are needed to provide the spatial distributions of GI more evenly.

We used Gini coefficient to analyze the spatial equity of GI. Regarding this spatial equity, a key finding is that local districts with prevailing (semi-)detached houses have a higher spatial equity of GI distributions. As a consequence, their residents can much easily access nearby GI for further recreation. This result is emphasized in so far as this structure type is socially dominated by middle-class residents (Banzhaf et al., 2018; Nuissl et al., 2005). The GI distributions are relatively unequal in districts prevailed by linear multistorey housing and perimeter blocks. In these residential areas, urban dwellers have a lower equity of potential access to the same amount of GI, compared to dwellers in districts predominated by (semi-)detached houses. This outcome 1) pictures the variations in the spatial equity of the GI distributions for different types of residential areas, and 2) reveals substantial impacts on potential recreation functions of GI.

Combined MSPA with spatial equity of GI serves to our novel exploration of the multiple relationships between spatial patterns and equity of GI distributions. In general, bridges that connect from one GI core to a different GI core have a significant influence not only on the GI structural connectivity (Clerici and Vogt, 2013) but also on the spatial equity of GI distributions. For each of the local sample districts, GI bridges and edges are the most important feature classes in support of the spatial equity of GI distributions, with a much higher impact than the GI core areas. GI bridges enhance the connectivity between GI cores and significantly increase equity on green spaces in linear multistorey housing estates, particularly in local districts with a relatively high Gini coefficient.

For instance, in Paunsdorf and Südvorstadt, the potentials of enlarging GI cores are limited to the lack of space. These findings clearly support strategic planning for networks as a main principle of the urban GI concept (e.g. Pauleit et al., 2017; Wang and Banzhaf, 2018). The strategies for better providing urban ESS need to consider 1) spatial patterns and morphology of residential areas, such as sharing long edges with green spaces such that many residents are close to them (Samuelsson et al., 2018), 2) the ecological connectivity of urban GI, so that both urban dwellers and the flora and fauna themselves could cognitively connect with the biosphere (Colding, 2007; Colding and Barthel, 2017).

Overall, the MSPA reveals considerable variations in the morphological spatial patterns of GI and the different levels of structural connectivity of GI across each of the typical residential areas. In the method used to calculate the Gini coefficient, we defined a 300 m buffer around residential areas. The 300 m threshold was quite influential to measure citizens' proximity to urban green spaces in many cities, such as Greater Manchester, UK (Kazmierczak et al., 2010), the City of Jeddah, Egypt (Khalil, 2014), and Shanghai, China (Fan et al., 2017). However, we cannot disclose the potential discrepancies if we set distinct thresholds. From this point of view, other creative methods, such as cognitive distance analysis by Samuelsson et al. (2018), the availability of residents to parks in their neighborhood by Poelman (2018), and the public participatory GIS (PPGIS) approach investigated by Samuelsson et al. (2018), Rall et al. (2019), and Samuelsson et al. (2019), may bring enriched insights to limit the uncertainties by cause of our methodology. Furthermore, inevitable uncertainties are associated with our MSPA, as discussed by Vogt et al. (2009) and Wickham et al. (2010), in the preprocessing of our derived land use and land cover dataset as well as in the use of the recently updated toolbox to acquire the GI morphological spatial patterns. To limit such uncertainties, we validated our methodology by first applying it to each local district individually, and then to each type of local districts. Although the use of empirical parameters, such as GI connectivity, edge width, and transition options, among others, with unknown degrees of uncertainty or possible variability introduces some inaccuracy to the outcome of our MSPA, our methodology is based on a well understood approach and has been applied to all sample local districts in the same manner. We aim to strike a balance in a substantial reliability and explore the morphological spatial patterns in typical residential areas. Indeed, this is the first time that the MSPA approach was used to analyze the GI structural connectivity in typical residential areas, and our application provides good examples for further interpretations of the spatial patterns of GI. Both parts (Sections 2.2 and 2.3) of our methodology that build on one another are transferable and traceable with respect to practicability in GI planning and assessment.

5. Conclusions

Three innovative aspects have been presented in this study: first, the application of the MSPA to the typical residential districts to analyze the spatial patterns of urban GI in a growing city; second, exploring the spatial equity of the GI distributions within the typical residential districts; and third, understanding the spatial equity of the urban GI from the morphological perspective.

A growing city like Leipzig encounters the options of either to enlarge the existing GI core areas or enhance the GI bridges, and meanwhile to reinforce the spatial equity of GI for sustainable urban development. Our study provides evidence that enlarging the existing GI core areas would only lead to a limited increase of the spatial equity of GI distribution and, therefore, appears to be less favorable. The option for GI bridges provides structural connectivity from one GI core to different GI cores. Hence, it will substantially contribute to the GI equity. This suggestion is attributed to our combined methodology of MSPA and GI equity measurement (GI-adapted Gini coefficient index). Following from this, urban GI planning should specifically strive to enhance connectivity. GI planning in essence is a strategic planned network to improve the structural and functional connectivity; therefore, it is significant that methods on MSPA and the analysis of the GI-adapted Gini coefficient can reveal the GI spatial patterns and distributions, enabling more informed clues to attain sustainability.

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