Urban green infrastructure for biodiversity and ecosystem services

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Chapter 6

General discussion

6.1 Evaluation of Green infrastructure as a multifunctional powerhouse

Green Infrastructure (GI) is believed to act as a multifunctional Nature-based Solution (NbS) in cities enriching biodiversity and generating ecosystem services (ES) simultaneously. In this thesis, I aimed to understand how urban GI acts as a multifunctional Nature-based Solution for climate, health and biodiversity challengethrough gathering comprehensive empirical field data —which were lacking— and adressing important knowledge gaps on urban GI multifunctionality. The evidence gathered shows that GI does provide ES and supports biodiversity. However, across the different studies, I showed clear evidence that ES and biodiversity do not have consistent synergies or trade-offs in urban GI, and rather that biodiversity and ES depend on different features of GI.

In chapter 2, I assessed the urban GI literature focussing on ES and biodiversity. During this assessment, I found that most of the GI literature covering a single taxon of biodiversity or a single ES contained unique GI types. For example, plant biodiversity literature uniquely considered the GI type of spontaneous vegetation, while research on water regulation included rain gardens. Alongside unique GI types, GI types covered by multiple biodiversity taxa or multiple ES were also present, such as park or forest. Forest and parks are known to encapsulated large quantities of variation in vegetation and are therefore likely related to multiple GI functions. The most commonly used GI types also tend to be from the most easily available data, suggesting that most research is driven by data availability, not by mechanisms that drive the phenomena of interest. I harmonized both unique and common GI types into the Consolidated Urban Green Infrastructure Classification (CUGIC), a two-part classification and mapping framework utilising both Remote Sensing and LULC maps, to assist research on urban GI multifunctionality.

In chapter 3, I used the CUGIC typology to assess the drivers of urban biodiversity by GI and its features. At the same time, I considered the impacts of anthropogenic stressors and the presence of water as important covariates. Most of the trained models performed better than random, yet lacked enough performance to traditionally be considered reliable. This suggests either that models miss important drivers of species' distributions, or that urban species' distributions are random-like (as proposed by neutral theory (Leibold and McPeek, 2006)). Nonetheless, the models that were better than random ones suggested that the presence of GI and its features are most important for understanding species' distributions. In contrast, anthropogenic influences showed little importance.

In chapter 4, I evaluated the drivers of urban biodiversity in façade gardens, including minute details on GI that are difficult to obtain using remote sensing data. Additionally, I paid special attention to the life history of the species and included GI features that may relate to it. The results suggest that insects in general, pollinating insects and herbivorous insects respond differently to different features of façade gardens. Across all GI features, coverage and plant species richness were the most important drivers of insect biodiversity. Additionally, pollinators respond well to indicators of food availability. This suggests that both the GI presence and GI composition are important to the communities that live in them.

In chapter 5, I returned to the locations of chapter 3, to gather data on ES considered important for urban environments. The results suggested that biodiversity and ESs are spatially distributed independently from each other. This corresponded well with results indicating different features of GI to be important for different ES. These results suggest that biodiversity and ES do not have synergies and trade-offs and that their driving forces are related to different GI features.

Given the above, I argue that to harness the power of GI to enhance biodiversity and ES, we need nuanced approaches to respect the individual functions and components that make up nebulous concepts such as GI, biodiversity and ES. Previous reviews already alluded to the importance of urban ecosystems functions, traits of organisms and its interaction with the urban environment, but empirical evidence was fully lacking (Schwarz et al., 2017; Zhang and MacKenzie, 2024). Core to the consistently found relationship between urban GI, ES and biodiversity seems to be overly large generalisations. These generalisations tend to ignore the nuances in the biophysical systems in favour of an easier "rule of thumb". For example, urban trees could be found to be related to insect richness. With some generalisation this would translate to urban GI is good for biodiversity. Indeed, some parts of GI (trees) are good for some parts of biodiversity (insect), but the initial result (tree - insect) does not provide good evidence for the extent of the generalised claim (GI - biodiversity). Thus, a nuanced approach to GI, ES and biodiversity which all contain a vast amount of structural, spatial and temporal variation is required to both understand and enhance urban GI multifunctionality, rather than blanket generalisations (Zhang and MacKenzie, 2024). However, I am under the impression that in the quest to deliver multifunctional solutions to major urgent urban sustainability crises, the acknowledgement of complex relations is overshadowed by generalizable quick fixes (van Oudenhoven et al., 2018; Garmendia et al., 2016).

In the following subsections, I will delve into answers to the individual research sub-questions from the introduction. Subsequently, I will discuss the implications for CUGIC and its place in future research, GI multifunctionality, and implications for society. Finally, I will provide conclusions on the presented research and discuss implications.

6.2 Reviewing the presented evidence

The aim of this thesis was to understand how urban GI, and its features, play a role as a driver of multifunctionality, covering biodiversity and ES. I subdivided this research objective into four sub-questions, which in turn, were covered by the four research articles in this thesis. In this section, I will address each individual research sub-questions and discuss how the main results help answer these sub-questions. The sub-questions were: I) how is the Green Infrastructure concept used across biodiversity and ES research, and is there a possibility to consolidate key Green Infrastructure classes from them?, II) how do GI, and its different features, drive urban biodiversity? III) How do GI, and its different features, drive urban ES?, and IV) do biodiversity and ES have synergies or trade-offs in GI?

Underpinning the thesis is GI, and I set out to understand what is meant by GI and its practical application in research. Understanding the GI discourse, definitions and operationalisation is the first step in cross-comparing and synthesising research results across all relevant disciplines needed to assess urban GI multifunctionality. I evaluated the literature across 9 different functions of GI: five ES: air temperature regulation, air pollution regulation, water regulation, physical health, mental health; and four taxa: mammals, birds, invertebrates, plants. This allowed for the evaluation of GI's role in the enhancement of ES and biodiversity. When comparing the usage of the GI concept across these functions, the results indicated that how GI was conceptualized, and how it was operationalised, varied across ES and biodiversity (chapter 2). For instance, GI can cover vertical greenery in climate studies, while it covers bioswales in water retention studies. Depending on the research discipline the GI quantification and features of interest change. Two plausible explanations for the variety in approaches might be that I) GI is a buzz-word that emerged after identification of already relevant drivers within a discipline and used interchangeably with these drivers afterwards. For example, urban biodiversity research showed parks as drivers of biodiversity, but only recently adopted under the GI umbrella. This may be done to appease policymakers who steer the research agenda and its funding (van Oudenhoven et al., 2018; Geukes et al., 2024). Alternatively, II) research using GI as predictor following the European Commission (2014) definition may produce negative or null results, and therefore may be less common as such articles tend to be more difficult to publish (Møller & Jennions, 2001).

A major underlying problem is that the popular usage of the GI definition provided by the European Commission (2014) —"a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings"— does not provide any realistic opportunity for consistent operationalisation. While initial intentions were to create an all-encompassing definition to benefit biodiversity and humans, the GI definition tends to be too ambiguous, hindering integral policy and potentially even harming biodiversity (Garmendia et al., 2016). Therefore, to allow proper operationalisation, I considered it critically important to harmonize the various ways in which GI had been classified across the different functions of GI. I extracted key drivers and concepts that remained consistent throughout the functions evaluated. This allowed us to present a harmonized perspective on GI, intending to provide a research framework and tool for interdisciplinary synthesis of GI and its relation to ES and biodiversity. This effort resulted in the Consolidated Urban Green Infrastructure Classification (CUGIC), a GI classification and mapping tool which is intended as a flexible system for global standardized research on GI. It leverages the already omnipresent usage of LULC-maps and utilizes satellite data focused on vegetation to provide both more variation and standardized quantification of GI.

Given that there seemed to be no consensus on the importance of GI features for ES and biodiversity, I decided to gather empirical data by doing fieldwork on these topics. I started with biodiversity and how GI, and its different features, impact its diversity, richness and species distributions. In this thesis, I assessed the GI-biodiversity relationship at both the landscape-scale, using the CUGIC-system (chapter 3), and the micro-scale, using façade gardens (chapter 4). This two-pronged approach allowed for investigating GI features at both the smallest and largest spatial scale in cities. Furthermore, this two-pronged approach also allowed for different level of methodological detail, coarse vs. fine, when assessing GI-features in relation to biodiversity. As a result, this approach demonstrated the importance of detail when quantifying GI features and its effects on predicting biodiversity.

Across these two chapters, the results show the GI presence as habitat is the strongest driver for biodiversity compared to other GI metrics. This result was consistent across all levels of analysis, yet the importance of GI presence in explaining biodiversity patterns changes with spatial scale and species groups of interest. Typically, it seemed that at the garden-scale the presence of extra habitat most strongly increased biodiversity. In contrast, this area-biodiversity relationship seems less important as a driver at large spatial scales. This may indicate a saturation point of the area-biodiversity relationship. In chapters 3 and 5, at large spatial scales much of the biodiversity remains unexplained by the included GI features. The explanation for the different area-biodiversity patterns may lay in the temporal dimension. For instance, large GI structures are managed more strictly and frequently by the municipality compared to management by homeowners. More evidence on different management regimes between private gardens and public urban green spaces would help evaluating this hypothesis (although some evidence is available on allotment gardens (Maćkiewicz & Asuero, 2021)).

In addition to the importance of GI presence, the importance of specific GI features varies strongly across scales. In particular, I found at large scales that spatial features from GI, using CUGIC, are a poor predictor for both species distributions and species richness, lacking strong explanatory power across taxa. In contrast, when including local-scale minute features of garden vegetation, such as flower characteristics and plant species richness and the local occurrence of pollinators or herbivores, the explanatory power of the models increased sharply (chapter 4). This increase indicates an important relationship of a GI feature with specific group of species. I argue that these results indicate that specific GI features that relate 1-to-1 with the life-history of species are the most important components in explaining biodiversity patterns. Following this argument, I also argue that sole application of coarse-scale general GI features, as done in most analysis (e.g. LULC or NDVI, see chapter 2), will only have a limited usefulness for understanding urban biodiversity, as they only correlatively capture the actual drivers of species requirements.

In chapter 5, I combined methods to assess the drivers of several ES that are important to cities. In particular, I questioned: “How do GI, and its different features, drive urban ES and biodiversity?”. Three ES important to the urban environment were measured: air temperature regulation, air pollution regulation and water infiltration. The results on air temperature regulation and air pollution regulation do support the notion that GI generally increases their regulation. And logically, although not tested directly, GI improves water infiltration, but not because of the presence of vegetation, yet rather through the absence of impervious surfaces. Concretely, the results of chapter 5 do show capacity for urban GI to support the generation of ES.

However, these results also indicate that these ES are all regulated by different features of GI. Interestingly, the impact of GI on any of the measured ES seems largely to be dependent on the physical attributes of the GI and environment (i.e. traits of leaves, soil features, etc.) rather than biodiversity metrics per se. Given the general understanding that different mechanisms drive these ES, this result is not unexpected but still novel. This does indicate that achieving multifunctionality is likely more dependent on finding the ideal mix of ecosystem attributes instead of enhancing biodiversity. Here, I argue, in a similar vein to biodiversity, that ES are better understood by including detailed mechanistic drivers that capture features of GI that are mechanistically relevant to the generation of urban ES.

Finally, I used the field-based observations on multiple ES simultaneously, supplemented with biodiversity data from the previous research. Combining these data, I aimed to more directly understand if GI hosts multiple functions that enhance both biodiversity and ES. The resulting analysis (chapter 5), shockingly, showed no synergies nor trade-offs among the ES and biodiversity data included in the analysis. In other words, I do find that some features of GI enhance ES and biodiversity, yet these results suggest that across a myriad of GI sites, ES and biodiversity are distributed independently from each other. This suggests that while the actual values of ES and biodiversity tend to correlate with GI presence, the driving mechanisms have different non-correlating spatial distributions. In turn, this resulted in the absence of synergies and trade-offs among the ES and biodiversity. This is the first evidence from field observations against the reigning GI multifunctionality paradigm and instead suggests distinct and unique relationships in the urban GI-biodiversity-ES nexus.

6.3 Is the CUGIC enough for assessing urban GI multifunctionality?

Throughout this thesis, I developed and applied CUGIC as a harmonized and consolidated classification system of urban GI. It brings GI features together that are used to characterise different functions that relate to urban GI multifunctionality. Specifically, CUGIC aims to create a framework that allows the study of GI multifunctionality, covering both ES and biodiversity. Such a system is necesarry as the mechanisms that drive biodiversity and ES are captured by uniquely different GI features, which all need to be considered in a holistic multifunctionality classification. Given that multifunctionality is the execution of multiple functions in the same spatial location and time, a classification —such as CUGIC— is needed to evaluate all functions simultaneously. CUGIC also allows for delineation among GI features thought to drive ES and biodiversity. In this thesis, the delineation was achieved by including multiple GI features simultaneously and assessing their importance and relationship with biodiversity and ES. From the evidence presented, CUGIC succeeds at delineating some relationships between GI features, ES and biodiversity (chapter 5), while lacking high explanatory power for urban GI multifunctionality.

Uniquely, CUGIC utilizes both LULC-maps —already omnipresent in urban GI studies— and indicators on vegetation density and the composition of height (chapter 2). Yet, the lower explanatory power of my models including CUGIC-indicators shows that it is missing large parts of the GI multifunctionality puzzle (chapters 3 & 5). While the CUGIC-indicators do relate to biodiversity and ES by mimicking variation in key features of GI, they seem to do this poorly. For example, vegetation density can indicate the presence of food availability, shelter, potential amount of evapotranspiration, etc. Yet, these features of GI do not have to co-occur, and my results (chapter 5) do provide evidence that driving factors of ES and biodiversity might not overlap.

The limited specificity of the data is inherently coupled to the aim for CUGIC to be a globally applicable system. A key advantage of the global scope is that it allows for cross-city comparisons, which are largely lacking, especially given the lack of such studies and some evidence that GI and its functions seem to behave differently based on climatic and cultural difference (Ochoa et al., 2022). On the one hand, this lack is due to the varying GI composition and functions across cities, and on the other hand because people value different functions of nature across different cities (Ochoa et al., 2022). Consequently, urban GI multifunctionality in Europe is likely different in form and value than in other parts of the world. However, the global scope limits the set of indicators as most data will be retrieved through remote sensing or open access data, which is limited in its availability to identify all unique features of GI that relate to multifunctionality.

The general globally applicable approach of the CUGIC thus lacks the details needed to explain both biodiversity and ES well. This may also be a result of CUGIC being built on GI features that were consolidated from multiple studies evaluating GI functions. This resulting CUGIC system reflects the commonly used and simple-to-gather indicators among a huge variety of studies using GI, that try to capture variety of natural processes. This means that CUGIC reflects agreed-upon indicators of GI features and their understood relationship to ES and biodiversity simultaneously. Importantly, CUGIC does allow for the delineation of importance among GI features as drivers of GI multifunctionality, but the inclusion of GI features that mechanistically drive separate aspects of biodiversity and ES seem to be lacking.

For CUGICs aim to assess GI multifunctionality, it needs to incorporate more indicators of mechanistic drivers for ES and biodiversity on top of the currently existing set of general vegetation indicators. Fortunately, novel techniques allowing for in-depth assessment of GI, biodiversity and ES are being rapidly developed and deployed. These techniques allow for quick data collection on features that were previously both labour-intensive and in-accessible to gather. For instance, data gathered traditionally with field work can be replaced by environmental DNA, street view features and climate sensor networks that are increasingly present (Ruppert et al., 2019; Kang et al., 2020; Gotovtsev, 2020; Muller et al., 2013). Such developments are happening on all fronts of the urban GI-biodiversity-ES nexus and will give an exponentially larger capacity to understand GI multifunctionality. For GI features, the increasing availability of street view data allows for the rapid retrieval of highly detailed photographs and extracting features of GI thought to be important drivers. Additionally, with the improvements to image segmentation algorithms, automating classification and feature extraction from such street view imagery, data extraction of important GI features is bound to happen quick than to traditional ecological methods (Kang et al., 2020). In short, this combination of global digital street-level digital imagery and the capacity of AI to classify GI feature automatically will allow us, in the near future, to create digital GI twins of cities across the globe.

At the biodiversity front, some of the novel methods that accelerated data gathering are DNA metabarcoding, AI classification algorithms and citizen science applications. These techniques allow for the rapid identification of species through capture of environmental, or whole organism, DNA and comparing DNA sequences to those in databases (Ruppert et al., 2019). This already allowed me to gather substantial amounts of data on species occurrences, yet still remains relatively labour intensive, and moreover quite expensive. Next to DNA-techniques, non-invasive biodiversity methods are increasingly developed, using other markers of species presence. Two interesting techniques are I) the use of sounds that species make as an identification method, requiring solely an extensive network of microphones (Zhao et al., 2022; Scarpelli et al., 2020, but privacy concerns). And II), the use of cameras to photograph and identify species as they pass by (Lopez-Vazquez et al., 2023; Yousef Kalafi et al., 2018). Separately, and somewhat passively, citizens are increasingly contributing to citizens science platforms gathering data on species presence, such as GBIF (2024). Currently, these techniques remains somewhat limited and biased in usage, but I am confident that —with some time— these techniques will set the new golden standard for capturing biodiversity data.

At the ES front, the developments are happening quickly, yet mostly unguided. Two of the most relevant ES in the urban system (air temperature and pollution regulation), are easily measured through sensors that may already be present in the homes or gardens of citizens or can be implemented in public spaces (Gotovtsev, 2020; Muller et al., 2013). Such a network, sometimes called the Internet of Things (Jamshed et al., 2020), can be comprised of governmental sensors and the sensors of residents of a city. Unfortunately, major barriers exist to gathering and combining data from all the sensor-devices that create the urban Internet of Things network (Kaginalkar et al., 2021). First, the data-ownership of citizens means that they do not have to share data. Second, the sensors used to measure temperature and pollution are different in their sensitivity and accuracy, and therefore requiring calibration among sensors to be somewhat useful or reliable. Third, a substantial amount of the sensors that exists are not linked to the internet or able to share their data without intervention of the owner. In contrast to air sensors, soil sensors are much less common. For water regulation, a network of soil-moisture sensors could help better understand the precipitation patterns and the capacity of GI to regulate water. However, most problems are present at impervious surfaces, where these sensors are not able to be installed. Here, cameras used for biodiversity can also identify flooding or other indicators related to water regulation relatively easily (Karanjit et al., 2023). Finally, outside the scope of the ES in this thesis, the increasing availability of data from social-media platforms and other sources on the web allow for relatively appropriate indicators on cultural ES, yet are to be fully utilised in urban multifunctionality studies (Cui et al., 2021).

Given the above, it is clear that the current approach in quantifying urban GI and its features is not detailed enough to explain both ES and biodiversity well. Simultaneously, novel technologies are rapidly developed that could help us better understand urban GI multifunctionality. However, bringing these data sources together, operationalising them and synthesising the results will be a substantial logistic and scientific hurdle. To better study urban GI multifunctionality and create sustainable and liveable cities, we need to prioritise this extensive data collection and start investigating GI multifunctionality in a more nuanced manner.

6.4 Implications for the urban GI multifunctionality concept

Substantial evidence suggests that GI demonstrates remarkable multifunctionality in natural areas, providing critical ES such as water filtration, flood regulation, and carbon sequestration, etc. simultaneously (Manning et al., 2018; Garland et al., 2021; Li et al., 2024; IPBES, 2024). The new IPBES Nexus Assessments even suggests urban GI as a NbS for similar problems in cities. However, the suggestions of urban GI being multifunctional (IPBES, 2024) is not in line with the results presented in this thesis. This differences could be explained by the literature and the empirical evidence shown in this thesis (chapter 2 — 5), indicating that urban nature is unique, and functions differently from natural ecosystems. The heightened anthropogenic influences (food availability, pollution, noise, presence of infrastructure, introduction of alien species, management, etc. (Kowarik, 2011; Aronson et al., 2017; Vilmi et al., 2021; Orr et al., 2022; McCloy et al., 2024)) result in a different composition, behavior and distribution of the species compared to rural or natural ecosystems (Kark et al., 2007; Kowarik, 2011; Leong et al., 2018; McKinney, 2006; McKinney, 2008). As a result, urban GI have been shown to be comprised of more generalist and alien plants and animals than in natural or rural lands (but not in agricultural lands (McKinney, 2006; Gong et al., 2013; Lokatis and Jeschke, 2022)). These functional difference are also assumed to be the driving factor in consistently found trade-offs and synergies between ES in urban GI (Zhang and MacKenzie, 2024). However, there remains a large knowledge gap in our understanding how urban GI and its biodiversity function differently form natural lands, resulting in mixed relationships between urban GI, ES and biodiversity (Schwarz et al., 2017). Therefore, I suggest, given the evidence presented in this thesis, to revise current ecological theories originating from natural ecosystems to better reflect the urban GI's distinct dynamics.

Potential driving factors that may help us understand the differences in urban settings are the fragmentation and degradation of urban green spaces and the heightened anthropogenic influences. In this work, I show that the quantity of GI and its features are key to biodiversity and ES. I find no evidence of effects of anthropogenic influences on biodiversity. However, all GI are human-made systems and are continuously influenced through direct (land management, weeding, pruning, etc.) and in-direct influences (noise, pollution, etc.). Within a context of continuous and omnipresent anthropogenic influences, variation in those influences may be less important. The combination of different drivers and species make that the theories developed in natural settings do not seem to work well in the urban environment. Therefore, it is essential to recognize urban areas as distinct ecosystems that require a different way of thinking to understand their capacity to deliver multifunctional benefits. Simultaneously, the benefits that are considered important in the urban ecosystem are different than the ones considered important in the natural system. For example, water purification is valued highly in natural systems, being the ES with the highest monetary contribution in the EU (Vysna et al., 2021), yet it is rarely considered as an urban ES (Li et al., 2023).

Given the contrasting results between GI multifunctionality in natural lands and cities and the distinctly appreciated benefits from GI, we need to further re-evaluate our understanding of GI multifunctionality. Acknowledging its weaknesses will help us develop new theories intended to better understand urban GI multifunctionality. One way to start such new theories, is by looking deeper into the traits of urban species and the functions they provide. Given that urban species are likely to have different traits than those in natural lands, synergies between functions (facilitated by the traits of the species present), as occurring in natural lands may be different or absent in urban systems. Moreover, the landscape level GI may be too fragmented or too limited to provide the full support for all species that may have been present otherwise. For instance, with some species and ES relying on large patches of GI (interior vs. edge species (Vanneste et al., 2024)) or the absence of some natural elements to fulfill their lifecycle (e.g. water for some insects (Balain et al., 2007)), not all functional diversity may be provided by the urban GI. The impacts of high level fragmentation, degradation and intensive anthropogenic influences of GI may help us understand why urban ecosystems work different than in natural areas.

To better understand the urban GI multifunctionality, we must develop new theories that consider urban ecosystem's unique ecological composition, spatial configuration and anthropogenic influences. Some theories are already being proposed aiming to incorporate these concepts and their impact on urban nature and its functions. For instance, the urban variant of the Social-Ecological-Technological framework aims to understand multifunctionality (McPhearson et al., 2022). At the meta-scale, it provides a relatively well constructed framework explaining the interactions between the urban ecosystem and its ecology. However, it lacks clear ideas on how ecological variation is key to ecosystem functioning and services. Instead, it provides some examples of how, for instance, green roofs and gardens provide different functions or services. Yet, this framework does not explain how these GI are ecologically different, and also vary amongst themselves, nor why these ecological differences matter for explaining the ecosystem functioning and services. Another novel ecological framework that has been proposed includes humans as ecosystem engineers of the urban GI and their effects on the biodiversity as a whole (Kendal et al., unpublished). It proposes the idea that humans actively favor certain traits that plants possess, explaining how humans shape urban GI by filtering species through both negative disturbances (mowing, pollution, etc.), and selecting and managing favored species (watering, weeding competition, etc.). Yet, it does not consider the benefits derived from the resulting urban GI. Beyond these theories, few researchers provide exciting ideas explaining the drivers and functions of ecosystems in cities in a holistic manner. Some theories exist acknowledging different elements of urban nature, but tend to remain abstract and focus on one topic. A popular example is the framework of Bartesaghi-Koc et al. (2016), consisting of four GI types aiming to explain most of the urban climate. This focus detracts from their power to understand both urban biodiversity and ES simultaneously. Creating a new holistic urban ecological theory and shifting perspectives on GI is necessary, but will require substantial research and validation through fieldwork, as proven successful for understanding natural ecosystems.

Underpinning a general urban multifunctionality theory is also the need to generalize across the globe. Literature on geographic-specific effects on GI composition in urban ecosystems are nearly completely missing, and may drastically change our understanding how it functions due to moderating factors such as culture, climate and environmental pressures. Humans actively shape the GI in the urban environments to their preferences; however these preferences are different for different groups of people based on ethnicity, culture, socio-economics status, demography, and etc. (Kendal et al., n.d.). Through this process, the implementation of GI based on local species preferences may result in a different composition of GI across the ethnic and cultural differences in the world (Nagendra, 2016). Similarly, climatic patterns have already been shown to impact the composition of GI when comparing arid regions with the Nordic region, where in arid GI has to survive water scarcity and in Nordic regions they are built for heat mitigation (Amorim et al., 2021; Ochoa et al., 2022). Combined, this evidence shows the need to also consider the different geographic drivers on GI composition and the follow-up effects on its multifunctionality.

With respect to previous urban multifunctionality research, much has been assumed and asserted without validation through fieldwork. As a consequence, many hypotheses, theories and models are used indiscriminately of whether they are reliable or robust, particularly from the viewpoint of multifunctionality. I show that the most commonly used indicators for urban biodiversity and ES models do not work well, indicating more complex relationships with urban GI. Achieving a better and more nuanced understanding of urban GI functioning will require both new theories of how urban multifunctionality works and intensive fieldwork on validating these theories.

6.5 Suggestions for a new theory of urban multifunctionality

Urban multifunctionality demands a more nuanced, ecology-centered approach than currently exists, with ecology being the primary driver of multifunctionality. Through my results (chapters 2 — 5), I demonstrated that understanding urban GI multifunctionality requires respecting the variation in GI and its features. Finally, we need to carefully examine GI features within their specific contexts and consider how they are socially valued.

A new theory on urban multifunctionality should start with urban ecology, by understanding how species are distributed and function, and how urban environments alter their behaviour. While ecosystems perform numerous functions, multifunctionality only emerges when specific ecosystem functions —deemed desirable by humans— coexist with desirable biodiversity. Thus, multifunctionality is about the overlap between biophysical processes themselves and human valuation. This situates ecology at the core, emphasizing biodiversity and context-driven ecological functions, while recognizing that multifunctionality is defined by human preferences rather than ecological capacity alone.

I propose to build on the urban SETs theory of McPhearson et al., (2022) and the urban plant trait framework of Kendal et al., (unpublished), and to view urban GI multifunctionality as a product of selected GI feature composition constrained by space, urban environmental context and human valuation (Fig. 6.1). In other words, urban multifunctionality is achieved when the GI feature composition provides multiple ecosystem functions that are desirable for humans in a limited amount of space (3D). This means that achieving urban GI multifunctionality is a result of selecting species that space-efficiently fit together, that comprise of the right traits, resulting in the right function and are valued by the people.

Yet, there are several constraining elements before GI features translate to GI multifunctionality. First (Fig. 6.1., urban environment constraints), in nature a certain combination of GI features may provide benefits, but these benefits can be constrained by the extreme urban climate or human behaviour. For example, trees may provide less capacity to cool off environments compared to rural ones as the water scarcity and temperatures are higher, reducing their evapotranspiration capacity (Peng et al., 2019). Likewise, food production may not be relevant as there are more health risks associated with urban agriculture (Salomon and Cavagnaro, 2022). In this way, the urban environment with its unique anthropogenic and climatic environment may limit GI multifunctionality. Second (Fig 1., ecosystem functions), when GI features trigger several ecosystem functions that may be considered ES, it could simply not be valued by citizens around that GI. This could either be as there is no need for that specific ES or because the people are not aware of the potential services of the GI function provided. Examples could be UHI reduction while people tend to stay inside with air conditioning, or limited cultural and health benefits as the exposure to GI and its features may be limited. Finally (Fig. 6.1., Landowner management), when GI does have the potential to provide several appreciated services, there can be a disconnect between the management as done by landowners and the desired management of potential beneficiaries of the GI ES. For example, a municipality may opt to mow, weed, clip or prune GI to help with visibility for traffic or to increase the sense of security. These actions then decrease the capacity for a GI to help with air pollution or temperature regulation, which may benefit the local citizens.

Therefore, urban GI multifunctionality is a a result of humans effectively designing GI resulting in a set of GI features that both I) have the capacity to thrive and function in the extreme urban environment and II) produce several ES valued by the varied groups of citizens.

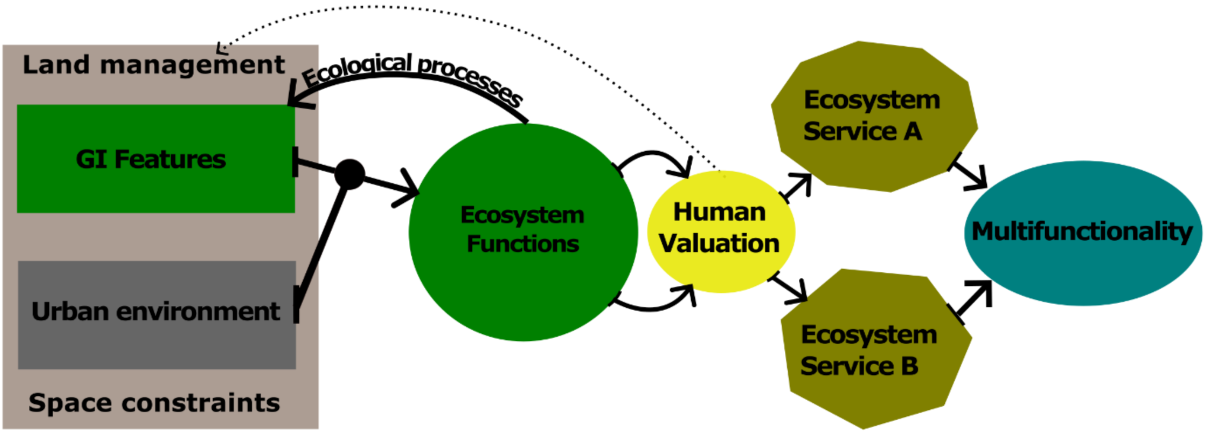

Figure 6.1. Theory on urban GI multifunctionality. Multifunctionality arises when a series of constraining layers are well adressed. Urban GI feature composition is the start of multifunctionality. It is a product of land-use management and prior ecological processes. Simaltenously, GI features are limited by space constraints and the functioning of GI is moderated by the urban environment it is embedded in. Ecosystem functions that do arise are then valued by the citizens that may benefit from them, which depend on socio-economic status, spatial and temporal proximity. Valuation may then also potentially influence future land management. When GI feature composition is correctly design to function in the urban environment and valued by the people it will provide multifunctionality.

6.6 Societal implications

Governments have globally agreed upon making cities sustainable and liveable as part of the Sustainable Development Goals (United Nations, 2015). GI, natural, and semi-natural managed areas, are proposed as a tool to achieve this goal, as they are supposedly able to space-efficiently execute multiple functions (i.e. multifunctionality) by delivering both ES —benefits that humans derive from nature— and enhancing biodiversity (European Commission, 2014). In this thesis, I show the opposite, I do not find any evidence or presence of multifunctionality of GI. Yet, I do find evidence that some features of GI are able to remediate some of the most urgent urban sustainability challenges. This is enforced by the results showing that GI functions tend to depend on mechanisms that are different for different functions. Given that GI is already increasingly used as a tool for decision-making, without concern for the nuanced relationships with biodiversity or ES, it is reasonable to worry about its reliability to produce accurate estimates of benefits provided by GI.

The results of this thesis suggest that for local governments, worldwide, the predicted benefits of GI may actually be considerably lower than expected. As such, targets related to sustainability issues will likely not be met. GI not providing benefits as expected seems to already be a large concern for practitioners working with ES assessment, with most agreeing that ES assessments should be more rigorous in testing and validation of ES indicators and assessment (n = 136, 91%; Forkink, 2017). Furthermore, different models estimating the same ES do not agree (Veerkamp et al., 2023). And, finally, validation of ES shows that substantial errors occur between predicted and actual ES in the field (Zhao and Sander, 2018; Rosenberger and Stanley, 2006). Both the current and future features of GI and their expected benefits must be locally re-evaluated and future plans to include GI as a NbS need to be re-assessed. At the same time, these results should not be interpreted as an argument to abstain from the implementation of GI, rather it should be a considered a warning to understand the actual capacity from the variety of GI systems to act as a NbS.

Importantly, I argue, that we strongly need to reconsider the temporal efficacy of GI compared to traditional infrastructure. Compared to traditional infrastructure, GI lives, grows and can die. This means that all of the functions that GI does carry out, which are important for cities to meet their sustainability goals, are dynamic. As such, at some points in time GI may provide multifunctionality when conditions are right, for example in summer with adequate water to sustain a healthy system, yet in winter with extreme droughts the green urban ecosystem may show reduced GI multifunctionality. Again, this is not an argument to consider omitting GI as a NbS to urban sustainability challenges, yet a cautionary example to illustrate the variability of GI multifunctionality under different climatic, temporal or environmental stressors that are typically dynamic in nature.

On a separate note but connected note, when reminded of the life outside academia, I wonder whether decisions on GI and urban planning are relevant to the perceived needs and concerns of citizens. During my field research in the city, I rarely met citizens who had air pollution, air temperature, water regulation or biodiversity as their key concern. This is clearly illustrated by the fact that local authorities prioritise mobility and climate adaptation, while citizens prioritise subsistence and safety (EUI team, 2024; Alsayed, 2024). Moreover, this is illustrated by the fact that there is a giant gap in research regarding what the citizens perceived needs are and what governments consider important (Alsayed, 2024). Realistically, if governments want to use urban GI for sustainability challenges, it may come across as tone-deaf when citizens are mainly concerned about their food security, safety, infrastructure, education and economic opportunity. Simply put, it is not relevant to talk about a street being protected from flooding when there is no dinner on the table. In this light, we need to be thoughtful on when and where to implement GI, as its implementation is dependent on political support from the electorate. Hence, we need to carefully balance the building and management of urban trees and, for example, funding food banks.

This also brings up crucial questions around equity and environmental justice in the context of urban GI planning. Given limited budgets for GI planning, efforts to do so should aim to both improve access to GI and should be grounded in the lived realities of marginalized communities. GI projects that fail to account for the spatial patterns of injustice risk exacerbating inequities through planning for GI in green neighborhoods while neglecting neighborhoods with mostly concrete (Langemeyer and Connolly, 2020). Simaltenously, consideration of equity doesn't limit itself to planning equal quantities of GI, but rather also consider the GI that meets the diverse needs of different communities (Langhans et al., 2022). This is important as many GI planning projects fail to address social inequities or environmental justice (Hoover et al., 2021).

Therefore, I argue that we need seriously reconsider whether the term ecosystem services is appropriate when we do not really consider the citizens needs and wants, at both the short and long time-scales. Furthermore, we need to study when and where GI is appropriate based on actual citizens needs and wants and find synergies with other citizens needs if possible.

Despite all of the above, GI should not be omitted as a potential Nature-based Solutions (NbS), rather complementary actions should be undertaken to either I) increase the capacity of GI to act as a NbS, or II) add in non-GI actions or infrastructure to meet the sustainability targets. First, to enhance the capacity of GI to deliver important ES can be enhanced through the smart connection with other GIs. This connectivity is known to support urban biodiversity (LaPoint et al., 2015), and also may help reduce the effects of stormwater run-off and the urban heat island through mitigating the build-up of hotspots of either of these problems. A GI may also not provide full benefits if the vegetation is not in good health. In this case, eco-friendly maintenance of the GI —not weeding, mowing or other destructive measures— such as watering and fertilizing soil may increase plants their efficacy in reducing heat, regulating water and supporting habitat for other species. Soil fertilizers may even be retrieved from the GI themselves, by collecting and composting the leaves that are traditionally discarded and incinerated. The use of fertilizers should be adjusted depending on the soil, its quality, vegetation in the GI and purpose of the GI. An extreme measure could be the changing of the soil to better fit the hydrological needs of the area. This could be achieved through partial replacement of the soil, which is potentially expensive. Similarly, soil aeration could be improved through an one-time use of invertebrate species, such as worms, that are known to provide substantial bioturbation, increasing the water regulatory capacity of the soil. On the social side, programs to involving citizens with GI maintenance, social activities or education have been shown to increase the appreciation of GIs. This can be achieved through the allocation of area as allotment gardens, festivals, food-markets, public lectures or tours through the GI. In these ways, good maintenance of the GI, its soil, one-time ecological intervention and involving citizens are potential contributors to enhancing GI performance as NbS for urban sustainability challenges.

Non-GI actions or traditional infrastructure may also synergize well with GI to tackle more complicated urban sustainability challenges. For example, water regulation of bioswale can be further increased by the introduction of typical stormwater management infrastructure. In this way, stormwater-runoff ends in the sewers, instead of flooding the streets when the bioswale has reached its functional capacity. Similarly, other smaller interventions such as rainwater barrels, can help with the interception of precipitation, while also releasing the water to the soil over longer periods of time. Such an approach can be especially helpful in arid regions, where water tends to be scarce for longer periods, impeding GI capacity to function. Infrastructure present in and around the GI, needed for its accessibility and maintenance, can also be adjusted to white or other reflective colors, and materials, to increase the GI heat regulating capacity further. Similarly, a variety of infrastructures is also important for making GI infrastructure accessible to the citizens who depend on them for social, cultural of health benefits. This includes roads, restrooms, drinking opportunities, parking and other facilities depending on the GI and its goal. These facilities can again be integrated with green roofs, walls, pavement and other GI technologies to further enhance the GI and its capacity to deliver ES. While these examples are somewhat few, a creative and GI-oriented vision will certainly provide more alternatives.

6.7 Conclusions

This thesis shows that the general approach to the urban GI concept is a poor basis for understanding its multifunctional enhancement of biodiversity and ES. In contrast, I show that unique GI features are paramount for understanding urban GI multifunctionality. GI as a policy concept aims to be a one-size fits all solution to urgent climatic and biodiversity challenges, yet its conceptualisation, operationalisation and thus benefits are inconsistent and unknown. Depending on the operationalisation of GI, there may or may not be relationships with biodiversity and ecosystem services, as these terms also encapsulate many different natural processes. Moreover, we do not understand urban GI multifunctionality well as reflected by the common usage of general GI indicators that tend to poorly explain urban biodiversity and ES. To understand urban GI multifunctionality, we need to pay respect to the individual aspects of urban biodiversity and ecosystem services and holistically integrate their drivers into a theory of urban ecology.

In the results (chapter 2 — 5), GI presence emerged as a dominant driver for biodiversity and ES across scales. In contrast to the currently existing multifunctionality paradigm, I found an absence of synergies or trade-offs between ES and biodiversity in urban GI. However, ES and biodiversity were uniquely driven by a variety of different GI features. These results affirm the need for a novel holistic and ecocentric theory of urban multifunctionality.

Despite these shortcomings to the urban GI multifunctionality concept, GI is capable of helping with several sustainability goals. Yet, I have found little evidence that GI helps substantially with several goals simultaneously. This indicates variety among urban GI, where some types work better for some challenges. Future research should focus on using new techniques, identifying driving factors and assessing the possibility to stimulate spatial co-occurrence of ES and biodiversity. Everything considered, urban GI provides more benefits than concrete and I encourage to mindfully incorporate as much green infrastructure in cities as possible.

6.8 References

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