Urban green infrastructure: perspectives on life-cycle thinking for holistic assessments

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Abstract. This article discusses the application of life-cycle thinking (LCT) methods for holistic urban green infrastructure (UGI) assessments to inform and enhance urban sustainability decision-making. It draws upon scientific and grey literature to present the key concepts and emerging LCT methodology developments within the urban green infrastructure evaluation context. Key methodological challenges are identified and discussed: the issues of (i) defining “green infrastructure” and (ii) “urban” boundaries, achieving (iii) the full representation of the broad range of UGI benefits and impacts (iv) over its whole life cycle, as well as (v) accounting for the wide variety of UGI types, their combinations and (vi) inherently dynamic nature, (vii) high performance dependency on climatic and other local conditions, and also, the challenges related to (viii) the monetisation of costs and benefits for comprehensive economic evaluation as well as (ix) the issues of city-scale assessments. Further methodology development and data needs for the adaptation of LCT methods for urban green infrastructure assessments are outlined. Four guiding principles are proposed: alignment with global urban sustainability goals, integration of ecosystem services accounting, harmonisation with existing LCA and LCC standards, and co-creation. The article concludes that urban green infrastructure is a novel field of application of LCT methods and differs considerably from traditional uses due to a range of methodological challenges specific to the inherent characteristics of urban green infrastructure. These need to be addressed in order to close the knowledge gaps and better understand the holistic value and performance of urban green infrastructure to enable evidence-based decision-making.

1. Introduction

It is recognised that urban green infrastructure (UGI) delivers multiple social, environmental and economic benefits contributing to urban sustainability [1–12]. However, policy- and decision-makers locally, nationally and globally lack reliable data and tools for assessing and understanding the full costs and benefits of UGI, which stalls uptake and limits access to funding for UGI development in cities [5, 6, 8, 10–13].

This paper discusses the application of life-cycle thinking (LCT) methods for the evaluation of UGI. The article argues for LCT as a viable methodological basis for assessing the holistic value of UGI accounting for the ecosystem services provided as well as costs and disbenefits generated throughout its lifetime. It supports the position of Petit-Boix et al. [14] who have argued that urban sustainability
planning and interventions, including the planning of urban green, would benefit from LCT-based quantitative assessments integrating environmental, economic and social facets.

The evidence base on methodological developments and practical applications of LCT methods for UGI assessments is sparse, limited in scope and scattered among various disciplines [14–16]. A conversation engaging experts on LCT methods, UGI and urban sustainability has not yet taken off. A previous review has shown that current attempts of applying LCT for UGI display significant shortcomings [14]; major gaps remain in both methodology development and practical application of LCT tools to UGI.

The objective of this article is to provide a starting point to the necessary discourse by presenting key concepts and principles as well as identifying and outlining key methodological challenges.

The definitions of UGI vary widely. They sometimes refer to natural or semi-natural ecosystems and at other times to man-made structures that are designed to be sustainable [17]. The focus of the present work is on the former and for this discussion urban green infrastructure is defined as: natural or semi-natural elements, systems or their networks within urban environment that provide ecosystem services. UGI encompasses a broad range of urban green types. In their classification, Bartesaghi Koc, Osmond and Peters [18] identify 41 (vegetated) GI subtypes grouped in 4 categories: tree canopy, open green spaces, green roofs and vertical greenery systems. Other authors commonly distinguish between autonomous green spaces and green elements integrated in buildings [14]. UGI is recognised to deliver a multitude of benefits for urban environments ranging from adaptation and mitigation of climate change, water management, to enhancement of biodiversity, food production, health and wellbeing benefits, recreational and cultural, as well as economic and social benefits [1–11, 19–22].

The term “urban” and the boundaries of it are likewise equivocal [23, 24]. The national state designation of an area as “urban”, and hence the GI placed within such boundaries is considered here.

1.1. Life-cycle thinking assessment methods
Life-cycle thinking (LCT) assessment approaches and methods were conceptualised in the 1960s-1990s with the purpose of determining the environmental impacts of commercial products and services [25–27]. It was envisioned that a widespread use of LCT methods will lead to transitioning from exploitative to sustainable development [28]. Initially LCA focused on assessing energy use, but constant methodology development lead to an expansion into a wide range of environmental and human health impact categories [29]. The areas of LCT applications likewise diversified, including applications for strategic decision-making, also relating to infrastructure and building design [29].

Four methods currently comprise the LCT toolbox. Life Cycle Assessment (LCA) is primarily used to assess environmental impact. Life Cycle Costing (LCC) focusses on monetary costs and benefits. Social Life Cycle Assessment (S-LCA) is a recent development for the assessment of social impacts. Life Cycle Sustainability Assessment (LCSA) intends to integrate all of the previous in order to achieve a holistic sustainability evaluation [14, 27, 30]. LCA and LCC are standardised by international standards [31–33].

Due to the increasingly holistic nature of life cycle assessments and the existing experience of applying the methods for other types of urban infrastructure, it is presumed that LCT methods present a viable methodological basis for holistic assessments of UGI.

Petit-Boix et al. [14] identified buildings, energy, food, green spaces and landscape, mobility, urban planning, waste and water as the key urban sustainability elements and relevant fields for LCT methods’ application. Among these, assessments in water management, waste management and buildings are most common, with the other areas, including green spaces, significantly lagging behind [14].

Recently, steps are also being taken to advance the methodology for city-scale assessments, which integrate all three sustainability pillars by employing LCA, LCC and S-LCA in combination as LCSA [14], or through the development of new LCA-based assessment methods [34]. This approach likewise benefits from the evaluation of urban sub-systems, including UGI.
1.2.  Current applications and limitations

Recent reviews [14–16, 35] and an additional literature search by the author reveal 21 publications that apply LCT to UGI assessments [22, 36–55]. More than half of those focus on green roofs (13 studies) [22, 37, 38, 41–43, 45, 49–51, 54–56], with a smaller number of studies assessing green walls (4 studies) [39, 43, 46, 47], nature-based water management measures (4 studies) [22, 40, 43, 45], parks (2 studies) [44, 53], street trees or a single tree (2 studies) [43, 44], and lawns (1 study) [52]. Evidently, the UGI integrated in buildings or other urban structures as well as UGI that acts as a direct functional alternative to grey infrastructure (mostly for water management) receives more attention than other UGI types such as parks, street trees, lawns and meadows, gardens, urban forests, etc. Thus, the lifetime costs and benefits of the latter remain significantly less understood. The scope of the studies likewise remains limited - 90% of the papers reviewed assessed only environmental (57% of papers) or economic (33%) lifecycle impacts and benefits, and only one included (limited) social considerations. Half of the authors focus on only one impact type, while the other half include a range of impacts, however, not reaching the full array of the documented benefits of UGI. Greenhouse gas emissions is the most assessed impact. The benefit side of the equation tends to be narrowed down to a single benefit, mostly evaluating reduced energy demand, water retention or flood management benefits. Furthermore, the life-cycle phases of UGI are unequally represented, with most studies inventorying the operational service life (95%) and installation phase (86%), while raw material extraction, manufacturing and end-of-life phases significantly lag behind (included in less than half of the publications).

In these early stages of applying LCT methods to urban UGI, the studies cannot be considered comprehensive life-cycle assessments, and none of them lead to triple-bottom-line results (which in line with similar conclusions of Petit-Boix et al. [14]). The evidence and examples remain few and scattered lacking full systematic overview of the current status of the LCT method development for the application in UGI assessments.

LCT methods are already complex undertakings when used in the fields they were initially developed for. Adapting them for the use in UGI assessments engenders a host of additional complexities. The purpose of this article is to identify the challenges of this adaptation, outlining how current life-cycle based UGI assessments have addressed them so far, recognising methodology development and data needs, and where possible proposing strategies to foster more comprehensive LCT in UGI. For the framing of the discourse a set of recommended guiding principles is established first.

2.  Guiding principles

2.1 Principle 1: Alignment with sustainable development goals and New Urban Agenda

The concept of “sustainability” emerged in the 1970s calling for a change of mindset away from exponential growth and exploitation of non-renewable resources [57]. By 1992 it was cemented as a global policy goal [58]. Three themes emerged, defining the “three pillars of sustainability”: balanced economic growth, living well within environmental limits, and ensuring social equity [59, 60]. Urban sustainability, the local governance equivalent, is “the economic, social, and physical organization of cities and their populations in ways that accommodate the needs of current and future generations while preserving the quality of the natural environment and its ecological functions over time” [58].

Global sustainable development and urban sustainable development is currently governed by two frameworks – the Sustainable Development Goals (SDGs) [61] and “The New Urban Agenda” (NUA) [62]. As decision-making on all governance levels progressively aligns with the global goals set by SDGs and NUA, there is an increased demand for evidence to guide urban planning decisions towards better sustainability outcomes. In the context of UGI assessments, it translates into the need for knowledge regarding the contribution of UGI to global urban sustainable development goals corresponding to all three pillars of sustainability. Therefore, the methodological developments and future assessments of UGI are advised to link closely to SDG and NUA frameworks and to reflect the effects of UGI on environmental, social and economic pillars.
2.2 Principle 2: Integration of ecosystem services accounting
According to the definition of UGI, it is a natural or semi-natural system that maintains natural functions. From the perspective of the society, these natural functions provide “ecosystem services”.

The term “ecosystem services” similarly to “sustainable development” emerged in the 1970s and undulated through several versions [63, 64] until it became established in international policies in its current form through the Millennium Ecosystem Assessment [65]. It defined ecosystem services as “the benefits people obtain from ecosystems” and proposed the classification of ecosystem services along their functional lines into four groupings: provisioning services, regulating services, cultural services and supporting services [65]. In 2014 “SEEA Experimental Ecosystem Accounting” framework set a starting point for creating the inventories of ecosystems, their quality and the services they provide.

The framework of ecosystem services and their classification specifically can be applied to identify and account for the full range of urban UGI benefits and impacts. Linking ecosystem services accounting with LCT methods as a second guiding principle would provide a solid systematic basis for comprehensive life-cycle assessments of UGI.

2.3 Principle 3: Standardisation
With increased adoption and use of LCA and LCC in the 1990s a harmonised approach was called for [25]. The Society for Environmental Toxicology and Chemistry (SETAC) was influential in framing the discussions and published the first Code of Practice in 1993, which kick-started the development of LCA standards within the International Organization for Standardization (ISO) and series of ISO 14040 standards for Life Cycle Assessment were published between 1997 and 2000 [25], revised in 2006 and every five years thereafter [66]. The standards for LCC in the context of built environment were added in 2008 and revised in 2017 [67]. While S-LCA and LCSA are not yet regulated by officially adopted standards, their methodology development closely follows the provisions of LCA standardisation [27].

The standards represent momentous work done by scientists, consultants and industry representatives over almost three decades. It ensures the quality, methodological clarity and comparability of LCA and LCC assessments. Comparability is of high importance in the context of UGI, as the decision-making on an urban scale would often need to make choices between dissimilar types of UGI or between green and grey infrastructure. In the light of the existence of widely recognised and adopted industry standards, any further development of a holistic LCT methodology for UGI assessments ought to build on the previous work and seek further harmonisation.

2.4 Principle 4: Co-creation
Historically LCT methodology development, a highly applied field, has benefited from collaborations between researchers and practitioners. An inclusive and collaborative process is likewise necessary to ensure the uptake of the LCT-based methods in UGI assessments.

Co-creation is an approach, which embodies the abovementioned principles of science-practice collaboration. It originates in commercial product and service development and has been applied to various innovation processes [68]. It is a “joint, collaborative, concurrent, peer-like process of producing new value, both materially and symbolically” [69] and “a process in which actors exchange resources and jointly create value” [70]. When applied to research, the “actors” are researchers working alongside stakeholders with the aim to collaboratively develop new knowledge for the benefit of all involved, moving away from one-directional “knowledge translation” for the use in decision-making towards multi-directional, transactional, application-oriented, context-specific “knowledge production” [71]. Employing the principles of co-creation in the methodology development for the assessments of UGI has the potential to ensure its high applicability, usability and alignment with decision-maker needs.

3. Challenges
Based on existing literature and current practice, eleven methodological challenges for the adaptation and application of LCT methods for UGI assessments have been identified and are discussed below.
Although this identification does not represent an exhaustive list of all methodological issues, it highlights the key aspects as a starting ground for further methodological conversations.

3.1 Challenge 1: defining urban green infrastructure

The definitions of UGI as natural systems differ widely due to various institutions, organisations, disciplines and authors placing emphasis on different aspects, characteristics or types of green infrastructure [19]. It has been described as natural [4, 14, 18, 20], semi-natural [6, 8, 11] or man-made [8, 72], open [17] or green [2, 6, 11, 17, 72], spaces [2, 6, 17, 19], features [2, 6, 11, 17, 19], or networks [2, 6, 8, 9, 11, 17, 19, 73] and connections [11], which deliver ecosystem services [1, 6, 8, 9, 11, 19] conserve and maintain natural values, such as biodiversity [6, 8, 9, 11, 17] and/or natural functions [17, 19, 73]. High-quality [2, 8, 9], multifunctionality [2, 17] and interconnectivity [1, 2, 11, 17, 72] are likewise seen as defining characteristics. Some [2] emphasise the deliberate strategic planning aspects to differentiate from wilderness natural areas. Furthermore, in the disciplines of urban design, landscape architecture and land conservation, green infrastructure is rather seen to be an approach [1, 3, 74] or a set of principles [73] for land use and its planning [1], land conservation [72, 74] or for addressing a specific urban issue [3, 73].

The practical application of LCT methods requires the definition of a clearly delineated “functional unit” [25]. Therefore, a definition that describes GI as a physical entity with defined functions is preferable over those referring to principles or approaches.

3.2 Challenge 2: large variety of UGI

UGI as defined above includes an extensive variety of UGI types. The current LCT studies cover a range of 12 different UGI types, loosely grouped in three categories: 1) multifunctional UGI integrated in building structures (green roofs and green walls): 2) multifunctional independent green areas or elements (parks, street trees, lawns, etc.); 3) UGI for the primary function of water/flood management (rain gardens, bioretention cells, swales, etc.). A systematic classification of UGI types by Bartesaghi-Koc et al. [18] identifies 41 vegetated UGI types, which accounts for areas or elements of uniform level of vegetation and species composition. On the ground, however, UGI is rarely uniform, mostly integrating a variety of vegetation types. As an estimation of the heterogeneity of green infrastructure, Bartesaghi-Koc et al. [18] calculate 102 theoretically possible permutations. This, however, does not yet include the further variations resulting from the diversity of species within each of the vegetation types and their mutual interactions.

In the current practice of UGI assessments this problem is typically circumvented by assuming a uniform vegetation cover consisting of one species. Some assessments have included scenario analysis or literature reviews comparing two or more alternative species or their combinations and have demonstrated high dependency of the outcomes on the planted vegetation mix [16, 37, 39, 40, 52]. This highlights the fact that different vegetation types and their species provide differing ranges and capacities of ecosystem services, as well as require varying levels of maintenance, translating into impacts and costs. Hence, the assessments assuming uniform composition of vegetation cover, while providing valuable knowledge of the performance of the specific species, for most UGI types are not likely to represent a holistic understanding.

This aspect is further complicated by the fact that several of the ecosystem services provided by UGI depend not only on the presence of flora, but also fauna, which so far has been completely omitted from the discourse on urban green infrastructure LCT assessments.

The existing classification efforts of UGI provide a valuable starting point, however, for the specification and characterisation of the UGI object a better adapted, multi-criteria classification would be needed to reflect the various variables of UGI characteristics and to arrive at a realistic representation of the ecosystem composition and services of UGI. If globally applied, the use of common classification would significantly increase the comparability across studies.
3.3 Challenge 3: defining “urban”
As shown above, the concept of “green infrastructure” does not necessarily imply urban context. Broader interpretations include any open biodiverse space that delivers ecosystem-services [75]. However, the characteristics of green infrastructure, the ecosystem services provided as well as the severity of impacts or scale of benefits are likely to differ between urban and rural areas. Thus, a clear demarcation of the “urban” is advisable for both methodology development and life-cycle based assessments.

Urban areas and their boundaries are typically defined either through their assigned administrative functions (state definitions of “city”, “town” and their administrative roles), size and/or density of the population, or functional features, the predominant economic activity(-ies) within an area (predominantly “non-agricultural”) [23, 24]. “Urban” is seen as a function of social elements, economic organisation and physical environment characterised by being primarily “built environment” as opposed to “natural environment” [23]. The “natural environment”, which is also “UGI”, is the minority land-use type within a predominantly “built environment”.

From the perspective of LCT assessments, the setting of system boundaries will likely necessitate a clear definition of “urban”, especially when the assessments are done on a city-scale. One approach is to consider the processes that are clearly placed within the geographical boundaries of the urban area (as defined beforehand) and those upstream and downstream impacts that are closely linked to the urban metabolism [14].

3.4 Challenge 4: defining the “life” of UGI
For the application of LCT methods the definition of UGI lifetime duration and break-down into phases is required. A comprehensive whole-of-life assessment requires the inclusion of all UGI life-cycle phases, however current assessments routinely omit one or several phases pointing to the lack of data and established industry practices [38, 40, 48, 51]. While some authors argue that the excluded phases would not have had significant impact on the results [41, 43, 51], others find non-negligible impacts throughout the lifecycle [39, 43, 48], and/or note significant differences in results when several scenarios for a particular phase are assessed [40, 43]. This calls for more evidence on the relative contribution of the various life-cycle phases of UGI and warrants the inclusion of all phases for fully comprehensive analyses.

Yet, there is no agreed definition of the lifetime of green infrastructure [53]. Standard LCT methodology life-cycle break-down could be applied [56]. However, while the initial stages from raw material extraction, plant cultivation to on-site installation and operational use of the UGI are comparatively straightforward, the final stage – “end of life” is not easily definable for some types of UGI, especially those not integrated in built systems - such as urban parks or grassy lawns, ponds, etc. [43, 53]

The lifespan for such UGI types as green roofs and green walls, closely integrated with man-made infrastructure, depends on the longevity of the underlying structures and materials, thus can be delineated. Though, the addition of UGI elements alters the durability of the materials and structures and needs to be accounted for - e.g. green roof assessments note that the addition of soil and plant material prolongs the lifespan of roof insulating layers by two to three times [37, 38, 42, 54, 55].

On the other hand, it could be argued that other types of UGI should be planned to be maintained for perpetuity as key elements of urban sustainability and integral parts of the urban system. This is feasible, considering that those UGI types that successfully mimic natural ecosystems, require minimal maintenance and do not depend on inherently impermanent structures are likely to survive beyond the lifetime of other urban infrastructure. Indeed, urban forests and parks dating from medieval period are still in existence in Europe and have been providing a range of benefits for urban dwellers for centuries [75]. Even upon abandonment, green spaces continue providing ecosystem services as unmanaged “novel ecosystems” [76]. For the LCT assessments of these types of UGI the omission of decommissioning stage may be justified; and the cut-off point may be defined based on the objective and purposes of the study. However, note that if a long lifetime is being assessed, the discounting to
calculate the net present monetary value in LCC assessments, may render the costs and benefits of each 
additional year negligible.

Especially for reliable LCT assessments comparing UGI with “grey” solutions, a decision on the 
lifetime included requires careful consideration. Several studies conclude that the comparative 
environmental or economic benefit is highly dependent on the longevity of the UGI solution, as most 
savings and benefits occur in the use phase [16, 36, 43, 47].

### 3.5 Challenge 5 – including full range of benefits and impacts

A range of 31 documented benefits or ecosystem services provided by UGI is found in literature loosely 
grouped into nine categories: mitigation of climate change, adaptation to climate change, water 
management, food production and security, biodiversity and nature conservation, economic benefits, 
health and well-being effects, recreational, cultural and aesthetic benefits, as well as social advantages 
[1–11, 19–22]. Yet, the reviewed UGI assessments on average consider less than three benefits. Half 
assess 1-3 benefits, one fifth consider 5-7 benefits and almost a third do not include benefits’ analysis, 
foCUSING on costs and burdens only. Even the most comprehensive of the assessments account for less 
than a fourth of the benefits UGI is likely to provide. The omissions are often recognised by authors as 
study limitations; and they flag the need for more comprehensive assessments, in some cases stating that 
the inclusion of the unaccounted benefits would significantly alter the results and the consequent 
decision-making [43, 52, 55, 77]. Thus, we cannot yet speak of the results of holistic UGI assessments 
and the full value of UGI largely remains unknown.

A fully comprehensive assessment methodology requires a clear classification of UGI benefits. 
While various organisations and researchers have provided significant contributions to the 
understanding of green infrastructure benefits [1–11, 19–22] a common agreement on their definition 
and classification, much less on metrics for quantification is missing. For addressing the complexity, the 
combination of LCA, LCC, and S-LCA into now emerging LCSA is a promising methodological 
approach, it is, however, still in its early stages of development and needs to be adapted to the specifics 
of UGI as discussed here. The complexity and high data demand raise the issues of data accessibility, 
compatibility and the practical usability of the methodology for urban decision-making. A careful 
balancing between the appropriate scope of benefits and impacts to be included in an UGI assessment 
and the burdens of data demand and complexity needs to take place whenever the goal, scope and system 
boundaries are being defined.

Assessments covering a broad range of benefits and impacts should also carefully consider the use 
of weighing and normalising the different impact and benefit categories. The highest or most costly 
impacts and benefits might not always align with the societal objectives. The use of weighing factors 
determined by policy priorities is one way forward [78], participatory multi-criteria analysis techniques 
can also be employed to define the relative weights, but will depend on the subjectivity of decision-
makers involved and the criteria selected [79]. Sensitivity analysis is therefore highly recommended to 
test different weighing sets.

### 3.6 Challenge 6 – accounting for social benefits and costs

Within the pool of reviewed LCT assessments of UGI, the social benefits and costs are the least studied 
impact category. Only one of the assessments reviewed [40] includes explicit consideration of labour 
impacts as a social aspect. A third of the authors recognise the social impact gap in their studies and 
unvaryingly emphasize social considerations as an important factor requiring further study. They 
strongly recommend inclusion of social impacts and benefits in future assessments or remind that the 
current LCA results need to be considered in the context of the social realm for decision-making 
purposes [14, 39, 40, 43, 52, 77].

The social LCA (S-LCA), which intends to include the social considerations into LCA methodology 
is one of the newest additions to the LCT toolbox. At this early stage some of the key terms including 
“social impact” are not yet defined in a standardised manner and researchers struggle to obtain the 
necessary data, often resorting to a limited range of indicators [80]. The currently available social impact
databases for S-LCA, namely Social Hotspots Database (SHDB) [81] and Product Social Impact Life Cycle Assessment database (PSILCA) [82], are highly product- and production-chain oriented and mostly account for the social effects resulting from the modus operandi of the actors within the value chain or sector; the data resolution is national or sectoral scale. This only partially applies to UGI specifics, where social benefits and impacts are not only occurring in production and maintenance activities as determined by participating actors, but to a large extent result from the ecosystem services provided by the living system itself. Moreover, UGI social effects take place on a city, neighbourhood, street and building scale, which current social impact databases are not designed to capture. Thus, for the development of holistic UGI assessment methodology, the accounting for social impacts and benefits requires substantial focus.

3.7 Challenge 7 - monetising UGI benefits

When decision-makers and practitioners call for UGI assessments, they often point to the need of understanding the holistic “value” of UGI [5, 6, 8, 12, 13]. Being able to quantify the value of UGI would enable them to back their decisions on UGI development and maintenance, attract the necessary funding and frame the “business case” for it. Establishing a monetary/economic value of UGI is however a highly complex problem, due to a large range of non-monetary hard-to-quantify benefits and services UGI provides to the society, such as benefits to human well-being, enhanced biodiversity or aesthetic value. LCC is designed to assess the costs involved and could serve as an overall framework [83], however, for it to be practically applicable, large inventory of monetary values of the full range of UGI costs and benefits is required, but is currently non-existent. While there are various methods and approaches for valuing ecosystem services [84], there is no agreement on their harmonisation into a consolidated approach. Furthermore, it is observed that the monetisation of UGI benefits often involves moral and value deliberations [84], which could preclude an agreement on unified set of methods as the most appropriate and providing best evidence. This likewise extends to the choice of discount rate. While in current studies applying LCC or its elements the discount rates range between 4% and 7% [22, 37, 44, 45, 48, 55], there are voices calling for the use of lower [85], declining over time (hyperbolic) [86, 87] or negative discount rates [88, 89] in assessments with long-term environmental, climate or social implications. It is a highly debated topic lacking a consensus. Among other considerations, it is increasingly being acknowledged that natural resources are likely to become increasingly scarce, therefore more “valuable” in the future and thus should not be discounted [87, 89]. Also, discounting the future societal costs and benefits runs contra inter-generational equity considerations [88, 89]. Application of LCC is further confounded by the value and pricing variables being context- and location-specific [5, 6]. Moreover, caution needs to be taken in integrated assessments of UGI to not double-count the costs and benefits in LCA and LCC parts of the assessment [84, 90].

3.8 Challenge 8 – the dynamic nature of UGI

The nature of UGI as a “living system” is that of dynamic change. It follows, that also the benefits and ecosystems services provided by UGI are constantly changing – both gradually and abruptly and in both increasing and decreasing trajectories [11, 65]. Therefore, the impacts and benefits throughout the service life/maintenance stage in an LCT assessment of UGI are not uniform or linear. Likewise, the dynamic changes in the relative distribution of the different species, each of varying maturity add to the complexity. To account for these changes, time-series observations are necessary of the same or very similar UGI element. Alternatively, a detailed understanding of the system dynamics and interdependencies within the UGI ecosystems and their services would need to be achieved through empirical data and complex systems modelling. In most cases neither would be available with the current level of methodology development and data availability. These limitations are evident in the reviewed UGI assessments – 4 of them have acknowledged the dynamic nature of UGI benefits and impacts [39, 40, 43, 91], but only one [39] accounted for time-to-maturity in their calculations. For most part, and likely due to the complexity and lack of data and methods, the dynamic nature of UGI and their ecosystem services is disregarded in the current applications of LCT to UGI assessments.
3.9 Challenge 9 – sensitivity to local conditions
Not only is the UGI intrinsically varying over time, it is also highly sensitive to a range of external locally-specific environmental conditions (defined by biogeographic regions) and human factors [5, 65], which determine the effectiveness and value of ecosystem services provided and influence the inherent dynamic changes of the UGI element discussed above. This leads to the results of UGI LCT studies being only narrowly applicable in a specific biogeographic region, geographic location, and the local urban conditions, which hinders comparability, transferability of data and generalised conclusions on the benefits and value of UGI infrastructure or its types. The authors of current UGI assessments almost uniformly emphasise the high location specificity of their results by acknowledging the dependency on local climatic conditions and applicability solely in the same or very similar climatic zones or biogeographic regions [15, 36–40, 42–45, 47, 50–52, 54–56, 77]. Three comparative studies have analysed the UGI performance under differing climatic conditions and all have arrived at results diverging dependent on the local climatic variables [22, 41, 46]. This indicates a prerequisite demand for local data in LCT assessments of UGI to ensure realistic results and provide reliable evidence for decision-making. Meaning that significantly more empirical studies and monitoring are necessary locally, which increases the complexity and resource demands for LCT assessments of UGI. Altogether it is likely to lead to a slowed down uptake of LCT for UGI assessments in practice.

3.10 Challenge 10– accounting for cumulative urban-scale impacts
While highly localised single-UGI assessments are important for decisions on a local or building scale, in order to enable strategic city-wide decision making on UGI, the evidence needs to be scaled up to the whole urban area. That is, however, not a simple sum exercise. UGI elements in a city are likely to interact in ways leading to the compound impacts and benefits to not be the sum or linear scale-up of the individual performances.

The discussion on the urban-scale LCT application challenges and solutions is emerging. Although some steps are being taken to assess the individual elements of urban sustainability (including green spaces) from LCT perspective, comprehensive urban scale assessments are lacking [14], likely due to their complexity; and integration of individual assessment results into global performance of green areas is yet to be addressed. Recently Alberti et al. [34] have proposed first steps towards city-scale LCT assessments by discussing the definition of LCA elements for cities as complex systems. A study of Chicago’s urban forests by McPherson et al. [44] applied ecosystem management approach to the whole urban area of Chicago, viewing highly local small-sale processes and UGI elements (such the planting of a single tree) as part of the city-scale urban forest ecosystem affecting larger-scale processes. Their extensive analysis showed that individual trees planted in private yards have a range of significant societal benefits that extend beyond their direct impacts on the immediate surroundings [44]. An integration of the comprehensive whole-of-life nature of LCT methods with urban scale eco-system approach is a promising way forward in methodology development for enabling urban-scale decision-making on UGI.

4. Conclusions
The application of LCT approaches for holistic triple-bottom-line assessments of urban green infrastructure is a viable way forward towards understanding the full societal value of UGI and its performance for urban sustainability contributing to informed decision-making at all urban scales. However, it is a complex undertaking and the necessary methodological developments and adaptations are still in their very early stages.

UGI assessments as an emerging new field of LCT method application raises specific challenges that need to be resolved, namely: the challenges of defining “green infrastructure” and “urban” boundaries, achieving the full representation of the broad range of UGI benefits and disbenefits over its full life cycle, as well as accounting for the myriad of UGI types and their combinations and inherent changeability as well as high performance dependency on climatic and other local conditions.
Monetisation of costs and benefits for comprehensive economic evaluation and the issues of scale for city-wide assessments add further methodological challenges. A significant research, methodology development and data collection work is needed to fill these gaps and advance the adaptation of LCT methods for UGI assessments.

While the article identifies and outlines the methodological challenges, governance-related aspects are also likely to play a significant role in the uptake of LCT-based evidence on UGI in decision-making and implementation. The success is highly dependent on whether the local governance systems are suited to capitalise the benefits of UGI, which requires an integrated cross-sectoral decision-making and a strategic oversight over the full lifecycle of the UGI. The local authority readiness to take up the LCT-based evidence on UGI requires further study.

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