On the contribution of nature-based solutions to address urban metabolism challenges

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Abstract

The use of a multi-scale life cycle sustainability analysis (LCSA) could advance the evaluation of ecosystem services (ES) supplied by nature-based solutions (NBS) to urban areas. However, current analytical LCSA approaches are still not able to assess how urban metabolism (UM) impacts (e.g. those derived from land consumption) influence ES supply by NBS. There is also a general lack of experimental methods, and available data, to account for the space-time-dependent interactions and feedback loops that occur among socio-economic variables and determine the UM of an urban area. Those interactions and loops depend upon endogenous and exogenous land use functions, stock and flow of natural resources, and the set of ES supplied within and to the urban landscape by NBS. Thus, a major research question arises, which is how to improve existing UM methodologies for the assessment of ES delivered by NBS using a LCSA approach. To contribute addressing these questions, the present paper aims to develop an integrated LCSA framework that acts as an epistemological roadmap to model, quantify and valuing ES associated with NBS in UM models. As a proof of concept, the framework is used to define a prototype of modelling system for UM based on system dynamics principles, which is formulated on two European municipalities (Siena, Italy; Esch-sur-Alzette, Luxembourg) located in different socio-economic and environmental contexts.

Keywords
Ecosystem services (ES); life cycle sustainability assessment (LCSA); nature-based solutions (NBS); system dynamics; urban metabolism (UM)

Introduction

The assessment of the urban metabolism (UM) has gained widespread popularity as an approach to reveal the most cost- and resource-efficient pathways to address social, economic, and environmental challenges of cities (Kennedy et al. 2011, Pincetl 2012, Cui 2018). UM studies typically quantify the flow of materials, water, nutrients, waste, and energy through urban areas and compartments (Ferrão and Fernandez 2013, Kennedy et al. 2014, Villarroel Walker et al. 2017). Such studies may help to inform built environment professionals (e.g. urban planners, architects) on the impacts generated by urban development practices and production & consumption activities on ecosystems and human health. In other words, the identification of the most relevant metabolic flows and the quantification of associated UM provide valuable assessment tools to support the sustainable planning and management of cities, allowing a short to long-term mitigation of their environmental impacts.

Studies on UM quantify resource, product, service and waste flows (and their changes) making use of mass balance and flow analyses, but also energy assessments (e.g. emergy), footprint evaluations, input-output and network analysis, and eventually life cycle assessment (LCA) (Elliot et al. 2019b). Most of these approaches model cities as a *black box*, but there are examples where flows and/or inner components of cities are differentiated (*grey box*, *network box*) until a certain level of detail (Beloin-Saint-Pierre et al. 2017). All these models broadly relate to a “life cycle thinking”, which is typically disclosed through the massive use of life cycle inventory data and/or impact assessment indicators (Petit-Boix et al. 2017, Ioppolo et al. 2019b, Maranghi et al. 2020). Embedding life cycle thinking in UM frameworks facilitates a more fit-for-purpose process-based approach to assessing complex and interrelated economic, social, and environmental urban issues. The development of an integrated assessment of economic, social and environmental aspects into a unique modelling framework has been the driver for the relatively recent implementation of the concept of life cycle sustainability analysis (LCSA) (Zamagni et al. 2012).

The LCSA framework can be used to enhance UM studies, providing a knowledge base, database and software infrastructure capable to assess how the interrelation of environmental, social and economic factors in urban systems affect the yield of metabolic flows and their dynamics (Albertí et al. 2017, Petit-Boix et al. 2017, Ioppolo et al. 2019b). However, so far UM studies explicitly oriented to combine the LCSA methodology and/or principles are very limited. This is likely because of the lack of consensus on how to assess the complex cause-effect relationships between the use of land, resources and products/technologies, and their actual impact (which might be either positive or negative) on the environment and socio-economic spheres, both at urban scale and outside.

Some challenges still hamper the advancement of UM modelling studies. In particular, the uncertainty to define short and medium-long term scenarios and the scarce consideration of ecosystem services (ES) as part of UM accounting (Elliot et al. 2019b). ES represent the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing: that is, the benefits that people derive from functioning ecosystems (Costanza et al. 2017). ES can be classified in the form of “provisioning services”, “regulation and maintenance services” and “cultural services” according to Haines-Young and Potschin (2018), and are typically associated with the presence of nature-based solutions (NBS) in cities (Babí Almenar et al. 2021). Because NBS can contribute addressing environmental, social and economic challenges in cities, building greater consensus and knowledge between LSCA, UM and NBS offers a valuable scientific baseline for advancing the assessment of urban ES.

This paper investigates the opportunity to improve the UM assessment taking advantage of the principles underpinning LCSA and urban ES assessment approaches. We believe such a framework can create a robust scientific background to contribute moving beyond the current theory and practical appraisal for sustainable urban development based on the analysis of UM. Our aim is therefore to outline a preliminary integrated assessment framework in the form of a roadmap to model, quantify and value urban ES as part of UM-LCSA studies, and as a possible solution to encompass the sustainability pillars of the LCSA framework. In this regard, the role of the NBS concept becomes crucial as NBS represent one of the main drivers and potential providers of ES in cities.

2 Methods

2.1 Definitions

Some key concepts related to our framework are first introduced below. This allows to make clear the terminology adopted in the paper and to position our approach in the spectrum of other methodological approaches and available definitions.

- Life cycle sustainability assessment (LCSA) is an advanced methodological branch of LCA created to expand the scope of the classical LCA methodology (typically focused on environmental issues) and hence to incorporate the three pillars of the sustainability concept into a unique harmonized analytical method, namely composed by LCA + LCC (life cycle costing) + S-LCA (social-LCA) (Kloepffer 2008, Sala et al. 2013a, Valdivia et al. 2013). In 2011, an alternative version of LCSA (Life Cycle Sustainability Analysis framework) was coined to accommodate the knowledge from different disciplines and to better link questions to models of analysis towards transdisciplinary values (Guinée et al. 2011, Zamagni et al. 2012). Nowadays, however, the *LCSA analysis framework* is only conceptually framed and still needs to be made fully operational (Halog and Manik 2011, Guinée 2016).

- The nature-based solution (NBS) is a recent concept still under discussion (Babí Almenar et al. 2021), which the European Commission describes - at p.24 (EC 2015) - as an *innovative application of knowledge about nature, inspired and supported by nature [that] maintain and enhance natural capital. They are positive responses to societal challenges and can have the potential to simultaneously meet environmental, social and economic objectives.* The framework proposed here uses this definition as a starting reference, acknowledging however the occurrence of several other definitions and interpretations of the NBS concept (Eggermont et al. 2015, Maes and Jacobs 2015, Kronenberg 2016, Pontee et al. 2016, Xing et al. 2017).

- Urban Ecosystem Services (hereafter just ES) are the services directly produced by ecosystems within urban areas or in their hinterlands, e.g. (Gómez-Baggethun and Barton 2013, Luederitz et al. 2015). The present work focuses on urban ES, but also includes those ES that flow naturally into the city, such as many provisioning services relevant for some economic activities and human consumptions (biomass, freshwater, food, …).

- Urban Metabolism (UM) is usually considered as the quantification of flows of materials, water, nutrients, waste, and energy of the *technical and socio-economic processes that occur in urban areas* (Kennedy et al. 2007, Kennedy 2012). However, making use of the expanded urban metabolism framework of Pincetl (2012) as a basis, the purpose of this paper is to discuss on the potential integration of demography, health, accessibility, equity, social well-being, and policy elements as part of an integrated LCSA-UM framework, through the consideration of urban ES and the development of scenarios based on NBS (see next section). Additionally, it is acknowledged that environmental processes as well as technical and socio-economic ones shall be integral part of an UM model.

2.2 Methodological steps

A transversal state-of-the-art analysis has been initially conducted to investigate the literature on LCSA, UM and urban ES (see Figure 1, step 1). This has permitted the identification of key connecting elements shared between those areas of knowledge as well as the major constraints to develop our modelling framework. While LCSA is a relatively recent methodological system and hence does not offer a large amount of literature evidence (Guinée 2016, Ioppolo et al. 2019b), the number of studies within the UM and ES domains is very large. Seminal articles in each area of knowledge (LCSA, UM, ES) have therefore been selected and consulted within the present research, focusing on theoretical approaches, frameworks, methods, and transdisciplinary case studies on urban sustainability.
In order to develop an integrated LCSA-based UM modelling framework that supports the quantification of ES using NBS-based scenarios, a multi-dimensional (*md*) mapping table has then been designed to ascertain the appropriate states and components necessary to assess urban ES. This *md*-Mapping Table has allowed to identify the main variables, attributes and properties of urban ES assessments starting from a selection of methodological approaches developed to disclose sustainability challenges in urban areas. To narrow the scope of this analysis and reduce the methodological complexity, only a selection of studies has been eventually taken as reference, which are represented by former 'critical review' analyses on UM, LCSA and urban ES (Figure 1, step 2). As a result of this state-of-the-art analysis, the key-issues included in the *md*-Mapping Table have been organised according to several dimensions (spatial, temporal and methodological), which can generally characterize or depict sustainability issues in urban systems and their study (Figure 1, step 3).

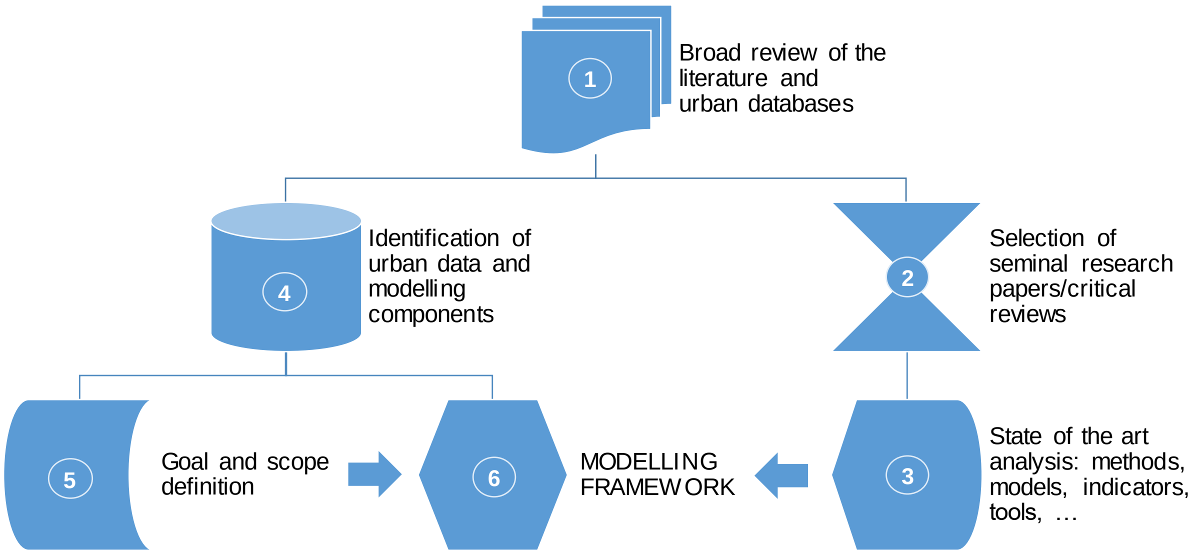

Figure 1. Methodological flowchart showing the key-steps and elements investigated for the creation of the proposed modelling framework.

The reviewed approaches have the potential to address LCSA and UM methodological challenges, while responding to policy questions on urban ES. An integrated approach for evaluating urban ES associated with NBS has emerged out of this *md*-Mapping Table by selecting features of LCSA and UM methodologies (Figure 1, steps 4-6). The validity of the framework has been eventually assessed against the following criteria: flexibility, replicability, coherence with purpose, credibility (scientific adequacy), legitimacy (capacity to produce fair and unbiased information), and saliency (relevance to decision making). The first four criteria are typically considered in land-use planning to ensure that assessment frameworks and their set of indicators are valid for different case studies (Boix et al. 2009, Recatalá and Sacristán 2014). The last three criteria have been proposed by Cash et al. (2003) and Nassauer and Opdam (2008) to assess the effectiveness of scientific information in societal decision-making processes, such as sustainable urban planning. This validation process has ultimately been performed by analysing two European cities taken as use case: Esch-sur-Alzette (Luxembourg) and Siena (Italy). While the two cities present different environmental, geographical and climatic characteristics (see Table 1), they have comparable dimensions and socio-economic features.

Table 1. Description of the city use cases.

	Esch-sur-Alzette (Luxembourg)	Siena (Italy)
Coordinates and climate (Köppen-Geiger climate classification)	49°30′08.2″N 5°58′52.9″E (Cfb: temperate oceanic climate)	43°19′06″N 11°19′53″E (Csa: hot-summer Mediterranean climate)
Yearly average temperature	10.1 °C	13.4 °C
Yearly average total rainfall	819 mm	777 mm
Height above sea level	287 m	322 m
Municipality area, population and population density	14.4 km^2, ~36’200 inhabitants, ~2’514 inhabitants/km^2	118.5 km^2, 53’922 inhabitants ~455 inhabitants/km^2
Main sources of data	The Luxembourgish Data Platform (https://data.public.lu/en/); municipality datasets (https://administration.esch.lu/); STATEC (https://statistiques.public.lu/)	Siena Open Data (http://opendata.comune.siena.it/); SIT (https://maps3.ldpgis.it/siena/); ISTAT (https://www.istat.it/)

The two cities have on-going urban development plans that aim to incorporate in future spatial managements and urban land use changes the notion of natural capital in the form of green infrastructure, such as new or restored urban parks, green walls and other green infrastructure systems (CdS 2020, VdE 2020). Hence, the rationale in this paper has been to analyse the feasibility of applying the proposed LCSA-based UM framework to studying the sustainability of Esch-sur-Alzette and Siena, because of their interest to implement specific NBS in order to capitalize on the associated urban ES.

3 Results and discussion

3.1 Findings from the state-of-the-art analysis

Figure 2, which represents the abovementioned *md*-Mapping Table, reports the studies selected for the state-of-the-art analysis and their links to the key-issues identified and used to formulate the framework for LCSA-based UM studies outlined in Figure 3. In other words, the items included in Figure 2 are those that can potentially be used to address the LCSA methodological challenges for policy questions on urban ES. The analysis of this literature reveals that there is a critical gap between current conceptual analytical LCSA frameworks and the development of applied approaches, methods and case studies to assess the impacts associated with urban systems as a whole. This is mainly due to a general lack of experimental models, decision support instruments and case studies able to account for the space- and time-dependent relationships among the components of UM (Beloin-Saint-Pierre et al. 2017, Elliot et al. 2018, Elliot et al. 2019a).

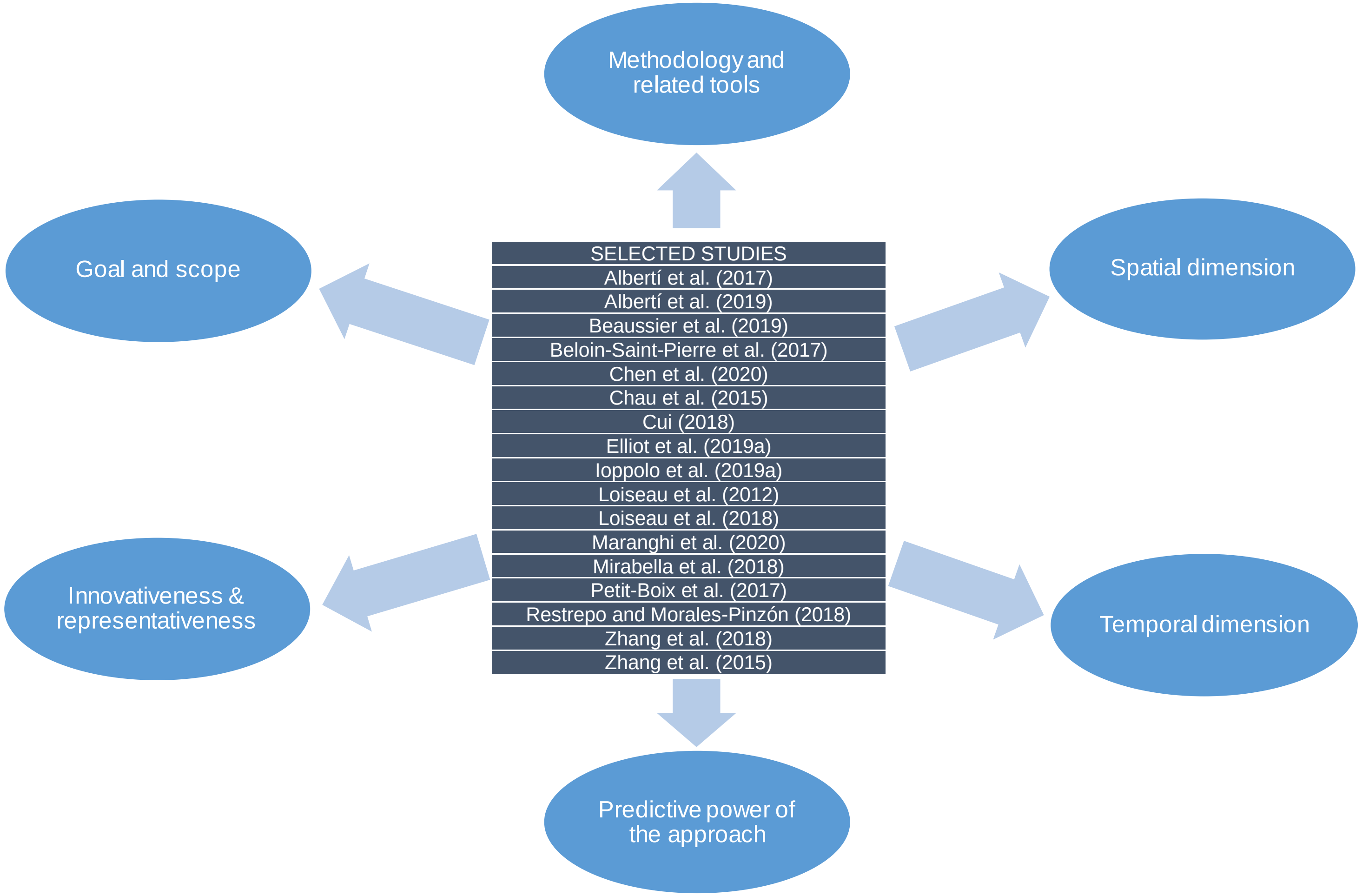

Figure 2. Studies selected and considered for the state-of-the-art analysis, and constellation of key-issues investigated for each of them; they represent relevant critical review literature focusing transversally on the topics of urban metabolism (UM), life cycle sustainability analysis (LCSA) and ecosystem services (ES).

In urban ecology, Alberti (2016) has identified similar methodological gaps to those highlighted in Figure 2, in particular with regard to the need for more research on social well-being and urban cross-site longitudinal data in order to advance the assessment of ecosystem functions (and services) of cities. The lack of urban data could be overcome by emergent research on urban big data (Batty 2013, Ferreira et al. 2013, Offenhuber and Ratti 2014) through the integration of well-distributed (spatially and temporally) urban information flows on socio-economic and ecological aspects (e.g. social perception of urban nature). Moreover, the current growth of literature on the mapping and quantification of ES at other spatial planning levels (e.g. Bukhard et al. 2012, Koschke et al. 2012), including examples from LCA, can suggest and guide towards the development of integrated frameworks and interdisciplinary research at urban scale. For example, in the LCA field Bakshi et al. (2015) and Liu et al. (2018) have built and applied an innovative methodological approach of coupled human-natural systems assessment in which ES supply and demand can be accounted for as associated with NBS. While Arbault et al. (2014) and Othoniel et al. (2019) have made progress in addressing the lack of accounting for interlinkages (economic, social, and environmental impact mechanisms) within the cause-effect modelling framework of LCA using an ES approach.

Additionally, limited forecasting capacity for many UM approaches has been identified (see Figure 2), although time dependency is a relevant factor in modelling complex systems like cities (Baynes 2009). As anticipated in Elliot et al. (2019a), several authors relate this to the complexity of modelling the intra and inter-linkages among the UM components and the limited time horizons and resolution of data used by many UM studies. However, an investigation of urban and environmental planning literature shows the increasing occurrence of participatory approaches (Reed et al. 2009, Ruiz-Frau et al. 2011, Susskind et al. 2012, Brown and Fagerholm 2015). Social survey data and expert workshops are promising solutions to complement historical time-series of urban data and help to generate external or strategic explorative scenarios, useful when a lot of uncertainty exists (Börjeson et al. 2006). Moreover, the literature on LCA shows an increasing number of case studies applying agent-model based modelling to evaluate specific spatial planning issues (Marvuglia et al. 2018, Marvuglia et al. 2020). This modelling technique, combined with data from participatory processes, can certainly facilitate the integration of different dimensions and key variables in order to allow the processing of large amount of information during scenario development (Börjeson et al. 2006).

On top of these aspects, the consideration of spatial factors was revealed as important as an acknowledgement of time-dependencies by many authors. According to Coelho and Ruth (2006), it is necessary to understand linkages of cities with other systems at the same, higher and lower spatial levels. In the same sense, Pincetl (2012) stresses the relevance of scalar relationships in UM, indicating that metabolism of cities are largely site specific, dependent on past and present factors of their context. Then, it is necessary to understand the level of dependency that different cities have on socio-economic and ecological factors of their sub-local, local, regional, national, and transnational contexts. This understanding will also facilitate the modelling of aspects such as demography, health, equity, social well-being as part of UM studies, relating them to changes in urban ES.

Regarding human-nature interactions, Sala et al. (2015), Costanza et al. (2016) and Othoniel et al. (2016) argue that the most suitable and effective approaches to allow understanding and quantifying the sustainability of human-driven systems are those that explicitly consider the nexus(es) among the human sphere/technosphere and the ecosphere. Alberti (2016) stresses the importance to understand those interactions as complex, not only complicated ones, which she indicates is a consequence of the presence of multiple networks of components in cities. According to her hypothesis, the structure and dynamics of networks defines the UM space, the rates at which energy, material and information are processed. She also indicates that on human-dominated systems, as cities, one needs to refine the way human-nature interactions are characterized representing them by gradients, patterns, processes, mechanisms, effects, legacies, and scales.

Regarding scales, systems at higher level (i.e. macro) shows characteristics and behavior that can hardly be understood from the observation and analysis of its main parts, at micro level (Beloin-Saint-Pierre et al. 2017). According to Gibson et al. (2000), this usually happens because there are causal relations or mechanisms which act at different scales, with feedback in the system. How to link these different levels (i.e. how many decisions at the micro level work out at the macro level) for the whole society remains an open question. Or, in the opposite sense, the question is about how to cascade global objectives down to individual actions and what will be the effect of each of the steps between (Guinée and Heijungs 2011). This is one of the problems at the core of sustainability assessments, which requires further sophisticated and broader models than traditional LCA. As a precaution until a better understanding of how to modelling UMs is gathered, Cash et al. (2006) propose to develop studies that include multiple spatial and temporal levels as well as research cross-scale interactions and effects, to avoid mismatches of scale. This eventually confirms that the sustainability modelling and assessment for urban systems is a broad concept that inevitably calls for a system-wide analysis. Complexity (i.e. multi-disciplinary knowledge, multi-spatial and time scales), uncertainty (i.e., many variables to take into account, and poor information and/or data available), and urgency (i.e. for mitigation processes of broad environmental and social challenges) are the main characteristics to be addressed in any sustainability assessment of urban regions.

3.2 Roadmap to multidimensional UM models based on LCSA

A step forward in the methodological development of LCSA is necessary in order to identify and evaluate properly system interrelations or linkages, and from here support the assessment of urban ES. Figure 3 depicts an advanced LCSA analytical framework that collects several pathways and questions necessary to address UM challenges. The diagram has been elaborated by merging previous LCSA conceptual frameworks (Guinée et al. 2011, Sala et al. 2013a, Dewulf et al. 2015, Sala et al. 2015, Guinée 2016). In this regard, modelling LCSA with an integrated assessment approach is the most promising way to allow for replicable and quantifiable sustainability analysis (Sala et al. 2015), adding credibility and trust to the decision process, increasing stakeholder confidence in their use and, if sufficiently flexible, enabling diverse decision contexts and the implementation of multiple modules, datasets and languages (Bagstad et al. 2013, Sala et al. 2015).

Former proposals to improve the computational framework of LCSA already include this integrated and dynamic modelling perspective (Halog and Manik 2011, Halog and Awuah 2013, Onat et al. 2017). For example, LCSAs applied in contexts of urban scale, such as for transportation systems, prove that the use of *system dynamics* is an effective strategy to capture causal relationships among social, economic and environmental parameters in macro level supply-chains (Onat et al. 2014b, Elsawah et al. 2017, Onat et al. 2017, Blumberga et al. 2018, Honti et al. 2019). Such an approach also shows the benefits of studying the mid and long term impacts of green building related policies addressed to mitigate carbon emissions (Onat et al. 2014a), or other impacts associated with urban air pollution (Vafa-Arani et al. 2014, Liu et al. 2015). Moreover, (Sala et al. 2013b, Sala et al. 2013a) clearly outline the key criteria (value choices, completeness of scope, geographical and temporal scale of the assessment, strategic value, methodology, participation of stakeholders) to enhance life cycle-based methodologies and to support the development of a next generation of LCSAs towards a mainstreaming of sustainability (as illustrated in Figure 3), i.e. the integration of sustainability concepts and requirements in each aspects of the methodology. To this end, adopting a system dynamics approach based on stocks and flows modelling is proven to be an effective response to the need to capture the complex intra- and inter-relationships among UM components (Elliot et al. 2019a). Consequently, an LCSA of UM models based on system dynamics features is a reasonable solution to encompass all the key-issues and methodological challenges underpinning a quantitative LCSA of products, technologies or broader functional units (e.g., final demand of goods and services consumed by urban communities). As pointed out by Schaubroeck (2018) this is recommended when the objective is to build an integrated assessment tool to model and analyse the sustainability of NBS using an ES approach.

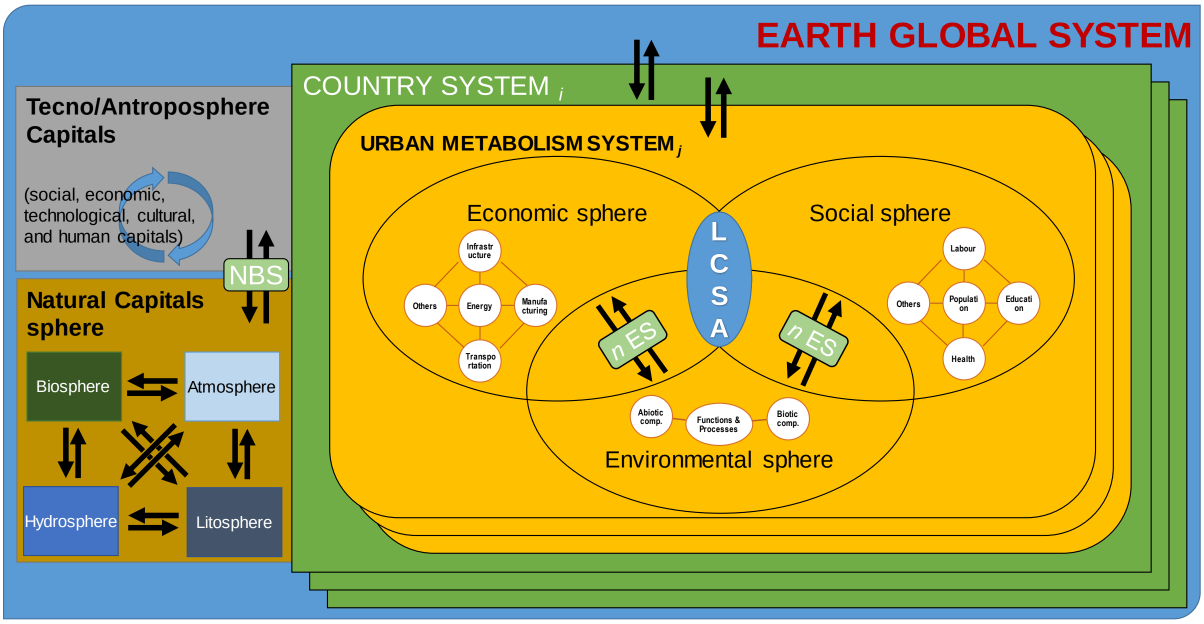

Figure 3. Framework for LCSA-based urban metabolism analysis focusing on ecosystem services (ES) as indicators capable to encompass the three spheres of the sustainability. Modelling the implementation of nature-based solutions (NBS) in such UM models can help expanding the scope of the scenario analysis since NBS typically generate ES, and are systems at the interface between the spheres of natural capital and techno/anthroposphere capitals.

Figure 3 suggests that LCSA-based UM models are not to be exclusively composed by linear input/output exchanges but shall also be governed by a comprehensive network of interactions and feedback loops which systematically occur among the key-UM variables within the investigated system boundary. In city landscapes, such variables are typically represented by socio-ecological structures, e.g. urban population, labour and capitals, access to public and private infrastructure and services such as mobility, leisure amenities, commercial and industrial facilities, etc. They necessarily depend upon endogenous and exogenous land functions, stock and flow of natural resources, and final ES supplied within and to the urban landscape.

As an outcome from the state-of-the-art mapping exercise in section 3.1 (Figure 2), three fundamental epistemological questions result to be addressed:

i) how to encompass the relationships among UM components analysed with a LCSA approach;
ii) how to design a methodology for the LCSA of urban ES;
iii) how to incorporate sustainable urban management policy issues in LCSA.

We believe that the development of an integrated modelling framework that assimilates the criteria proposed in Figure 3 might help addressing these questions through a quantitative application. The conceptual workflow included in Figure 4 displays the modelling structure and input/output requirements for Esch-sur-Alzette (Luxembourg) and Siena (Italy). This may be considered in the future as the knowledge database and system boundary to develop an LCSA-based UM model for the two cities. Accordingly, a feasibility analysis has been conducted to support the development of such modelling frameworks, as illustrated in Table 2 through a qualitative scoring exercise.

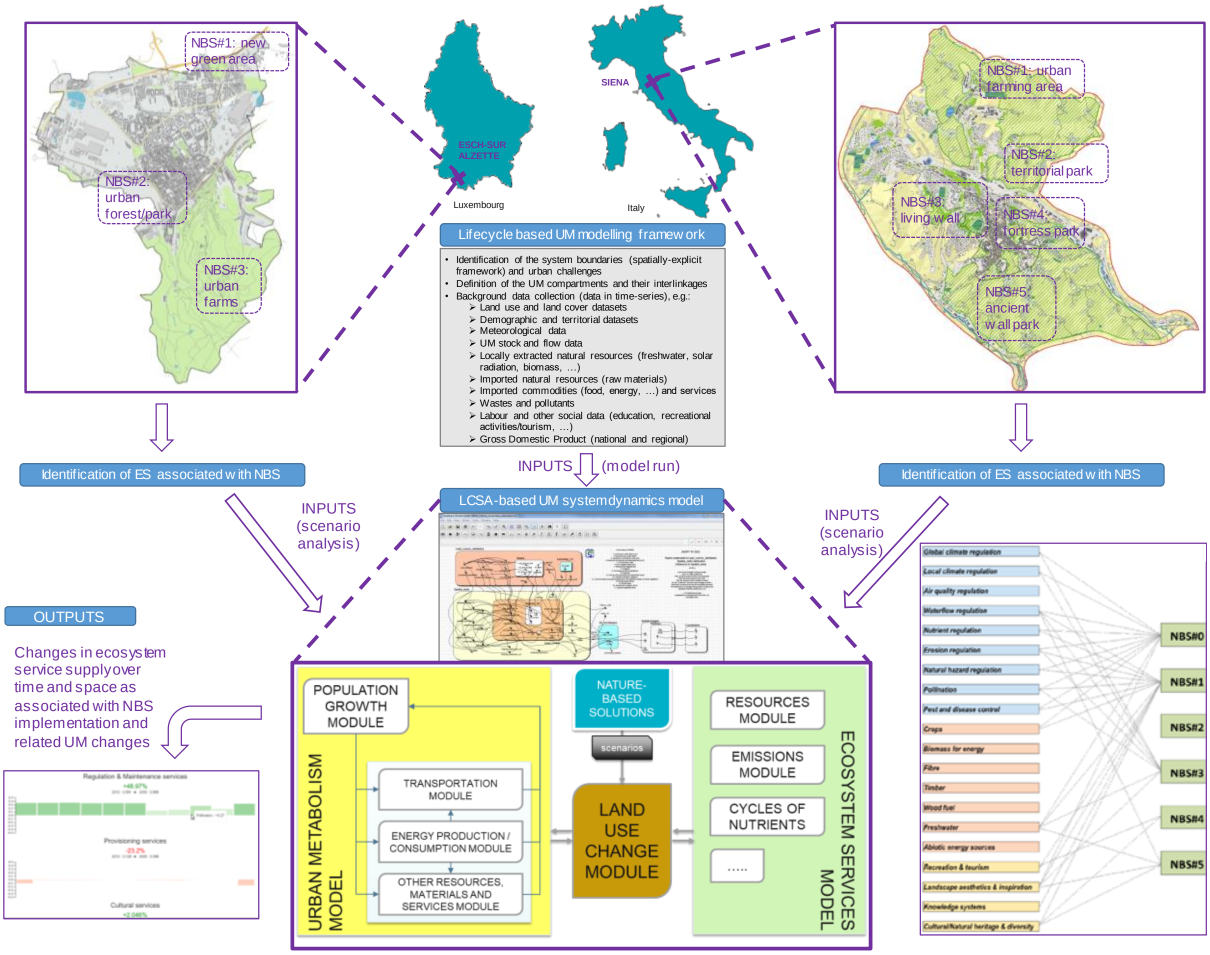

Figure 4. Comparison between the LCSA-based UM framework applied to the city models of (a) Esch-sur-Alzette in Luxembourg and (b) Siena in Italy.

Table 2. Qualitative feasibility analysis (Likert-type scale ranging between 1 and 3, where *1=low*, *2=medium*, *3=high*) underpinning the application of the proposed LCSA-based UM framework to the use cases of Esch-sur-Alzette (Luxembourg) and Siena (Italy).

Application of the modelling framework	Esch-sur-Alzette (Luxembourg)		Siena (Italy)	
Flexibility	3	The city is undergoing relevant urban infrastructure and land use changes in the last year, which make the application of several NBS scenarios possible without any remarkable urban planning constraint.	1	The historic centre of Siena is part of the UNESCO world heritage list, which makes urban land use changes in the city extremely limited. Therefore, only few NBS scenarios can be set up.
Replicability	2	The Esch's model can be considered quite replicable at the scale of Luxembourg and similar post-industrial areas that may undergo substantial urban land use changes.	1	Because of the specific characteristics of the UM in Siena (e.g. ancient historic centre, low urban development, etc.), the model might be low replicable to other contexts.
Coherence with purpose	2	Stakeholders from the municipality have shown some interest in the concepts of NBS and ecosystem services approach.	3	Stakeholders from the municipality have shown a relevant interest in the concepts of NBS and ecosystem services approach.
Credibility (scientific adequacy)	1	Data need to be searched and cleaned with accuracy, since most of them are aggregated at the national scale and/or are not freely accessible.	2	Access to data and availability is largely allowed which makes the development of the model potentially facilitated, its structure quite robust, and its outputs ideally not too uncertain.
Legitimacy (capacity to produce fair and unbiased information)	2	The above limitation on the data may generate some uncertainty in the outputs due to data treatment processes and results credibility.	3	Because of the data accessibility and availability, and an urban planning that already incorporates NBS related information, it is expected that the model may produce a set of high-quality results.
Saliency (relevance to decision making)	2	Operating the LCSA-based UM in Esch may be more considered a valuable modelling exercise rather than a policy-oriented support system.	2	The current urban development and management plan of the city may not be able to host new NBS implementations originated from a decision-making exercise based on the Siena's model.

4 Conclusions

Among the variety of methodological combinations depicted by the multi-dimensional visualization diagram, *system dynamics* is considered a promising and very useful approach to respond to the challenge of creating a spatially and temporally resolved UM analytical framework for the assessment of urban ES, where LCSA principles are satisfied (i.e. the need to address social, economic and environmental dimensions in the same data inventory and impact assessment framework). A critical review of literature crossing the LCSA, UM and ES assessment fields has shown that such a technique is able to capture in one unique relational framework the three dimensions of the sustainability concepts, allowing to model with a stock and flow information structure both macro- and micro-economic variables, social data and factors and environmental aspects and indicators. On top of that, different spatial configurations, georeferenced systems, time series datasets and temporal assessment resolutions can also be incorporated in a system dynamics model formulated for urban ES analysis.

This paper has further shown that the LCSA analysis framework owns the appropriate flexibility and infrastructure to support policy development and decision-making with regard to urban scale challenges and sustainable spatial planning, e.g. recovery of degraded urban land, enhancement of mobility services and processes, environmental impacts' mitigation, sustainable infrastructure development, consumption & production, etc. In this regard, the inclusion of a multi-scale system dynamics model of NBS to support ecosystem service management in urban systems is ideally an effective solution to consider LCSA concepts, data and indicators, while broadening the assessment towards a non-linear conceptualisation of cities as landscapes.

In order to intensifying sustainability awareness in urban planning and decision-making, some archetypal scenarios of nature-based solutions' implementation in cities have been anticipated here to support the definition of an epistemological roadmap, using two European small cities as testbed. The comparison has been conducted using a qualitative analysis that informs on how changes affecting the UM at different configuration scales (building, neighbourhood, municipality, etc.) can bring to changes in the supply of urban ES over future times. Such a prospective approach may eventually allow to support the development of a quantitative consequential LCSA modelling approach based on the formulation of an integrated multi-scale dynamic UM framework, which can incorporate knowledge on NBS implementation's scenarios for the quantification of ES.

Acknowledgements
Authors would like to acknowledge funding from the National Research Fund (FNR) of Luxembourg (CORE project "ESTIMUM" - C16/SR/11311935; www.list.lu/en/project/estimum/).

References

Albertí, J., A. Balaguera, C. Brodhag, and P. Fullana-i-Palmer. 2017. Towards life cycle sustainability assessent of cities. A review of background knowledge. Science of The Total Environment **609**:1049-1063.

Albertí, J., C. Brodhag, and P. Fullana-i-Palmer. 2019. First steps in life cycle assessments of cities with a sustainability perspective: A proposal for goal, function, functional unit, and reference flow. Science of The Total Environment **646**:1516-1527.

Alberti, M. 2016. Cities that think like planets: complexity, resilience, and innovation in hybrid ecosystems. University of Washington Press, Seattle and London.

Arbault, D., M. Riviere, B. Rugani, E. Benetto, and L. Tiruta-Barna. 2014. Integrated earth system dynamic modeling for life cycle impact assessment of ecosystem services. Science of The Total Environment **472**:262-272.

Babí Almenar, J., T. Elliot, B. Rugani, B. Philippe, T. Navarrete Gutierrez, G. Sonnemann, and D. Geneletti. 2021. Nexus between nature-based solutions, ecosystem services and urban challenges. Land Use Policy **100**:104898.

Bagstad, K. J., G. W. Johnson, B. Voigt, and F. Villa. 2013. Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services. Ecosystem Services **4**:117-125.

Bakshi, B. R., G. Ziv, and M. D. Lepech. 2015. Techno-Ecological Synergy: A Framework for Sustainable Engineering. Environmental Science & Technology **49**:1752-1760.

Batty, M. 2013. Big data, smart cities and city planning. Dialogues in human geography **3**:274-279.

Baynes, T. M. 2009. Complexity in urban development and management. Journal of Industrial Ecology **13**:214-227.

Beaussier, T., S. Caurla, V. Bellon-Maurel, and E. Loiseau. 2019. Coupling economic models and environmental assessment methods to support regional policies: A critical review. Journal of Cleaner Production **216**:408-421.

Beloin-Saint-Pierre, D., B. Rugani, S. Lasvaux, A. Mailhac, E. Popovici, G. Sibiude, E. Benetto, and N. Schiopu. 2017. A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. Journal of Cleaner Production **163**:S223-S240.

Blumberga, A., G. Bazbauers, P. I. Davidsen, D. Blumberga, A. Gravelsins, and T. Prodanuks. 2018. System dynamics model of a biotechonomy. Journal of Cleaner Production **172**:4018-4032.

Boix, L. R., J. S. Díaz, A. P. Soriano, and M. S. Sempere. 2009. Indicadores e índices integrados en la agenda 21 local para la evaluación de la calidad ambiental en áreas afectadas por desertificación del ámbito mediterráneo. Fundación Biodiversidad. Universitat de Valencia.

Börjeson, L., M. Höjer, K.-H. Dreborg, T. Ekvall, and G. Finnveden. 2006. Scenario types and techniques: Towards a user's guide. Futures **38**:723-739.

Brown, G., and N. Fagerholm. 2015. Empirical PPGIS/PGIS mapping of ecosystem services: A review and evaluation. Ecosystem Services **13**:119-133.

Cash, D. W., W. N. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, and O. Young. 2006. Scale and cross-scale dynamics: governance and information in a multilevel world. Ecology and Society **11**.

Cash, D. W., W. C. Clark, F. Alcock, N. M. Dickson, N. Eckley, D. H. Guston, J. Jäger, and R. B. Mitchell. 2003. Knowledge systems for sustainable development. Proceedings of the National Academy of Sciences **100**:8086-8091.

CdS. 2020. Piano Operativo (PO) - Relazione sul territorio rurale e gli assetti agrari. Available at: https://maps3.ldpgis.it/siena/sites/siena/files/po_ps/adozione/po_si_relazione_territorio_rurale.pdf. Comune di Siena (CdS), March 2020, Italy.

Chau, C. K., T. M. Leung, and W. Y. Ng. 2015. A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. Applied Energy **143**:395-413.
Chen, S., H. Long, B. D. Fath, and B. Chen. 2020. Global Urban Carbon Networks: Linking Inventory to Modeling. Environmental Science & Technology **54**:5790-5801.
Coelho, D., and M. Ruth. 2006. Seeking a unified urban systems theory. WIT Transactions on Ecology and the Environment **93**:179-188.
Costanza, R., L. Daly, L. Fioramonti, E. Giovannini, I. Kubiszewski, L. F. Mortensen, K. E. Pickett, K. V. Ragnarsdottir, R. De Vogli, and R. Wilkinson. 2016. Modelling and measuring sustainable wellbeing in connection with the UN Sustainable Development Goals. Ecological Economics **130**:350-355.
Costanza, R., R. de Groot, L. Braat, I. Kubiszewski, L. Fioramonti, P. Sutton, S. Farber, and M. Grasso. 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosystem Services **28**:1-16.
Cui, X. 2018. How can cities support sustainability: A bibliometric analysis of urban metabolism. Ecological Indicators **93**:704-717.
Dewulf, J., L. Mancini, G. A. Blengini, S. Sala, C. Latunussa, and D. Pennington. 2015. Toward an Overall Analytical Framework for the Integrated Sustainability Assessment of the Production and Supply of Raw Materials and Primary Energy Carriers. Journal of Industrial Ecology.
EC. 2015. Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities - Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities' Directorate-General for Research and Innovation 2015 Climate Action, Environment, Resource Efficiency and Raw Materials EN (full version). European Commission, Brussels.
Eggermont, H., E. Balian, J. M. N. Azevedo, V. Beumer, T. Brodin, J. Claudet, B. Fady, M. Grube, H. Keune, P. Lamarque, K. Reuter, M. Smith, C. Van Ham, W. W. Weisser, and X. Le Roux. 2015. Nature-based solutions: New influence for environmental management and research in Europe. GAIA **24**:243-248.
Elliot, T., J. B. Almenar, S. Niza, V. Proença, and B. Rugani. 2019a. Pathways to modelling ecosystem services within an urban metabolism framework. Sustainability (Switzerland) **11**.
Elliot, T., J. Babí Almenar, S. Niza, V. Proença, and B. Rugani. 2019b. Pathways to Modelling Ecosystem Services within an Urban Metabolism Framework. Sustainability **11**:2766.
Elliot, T., B. Rugani, J. Babí Almenar, and S. Niza. 2018. A proposal to integrate system dynamics and carbon metabolism for urban planning. Procedia CIRP **68**:78-82.
Elsawah, S., S. A. Pierce, S. H. Hamilton, H. van Delden, D. Haase, A. Elmahdi, and A. J. Jakeman. 2017. An overview of the system dynamics process for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies. Environmental Modelling & Software **93**:127-145.
Ferrão, P., and J. E. Fernandez. 2013. Sustainable Urban Metabolism. MIT Press.
Ferreira, N., J. Poco, H. T. Vo, J. Freire, and C. T. Silva. 2013. Visual exploration of big spatio-temporal urban data: A study of new york city taxi trips. IEEE transactions on visualization and computer graphics **19**:2149-2158.
Gibson, C. C., E. Ostrom, and T.-K. Ahn. 2000. The concept of scale and the human dimensions of global change: a survey. Ecological Economics **32**:217-239.
Gómez-Baggethun, E., and D. N. Barton. 2013. Classifying and valuing ecosystem services for urban planning. Ecological Economics **86**:235-245.

Guinée, J. 2016. Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges? Pages 45-68 *in* R. Clift and A. Druckman, editors. Taking Stock of Industrial Ecology. Springer International Publishing.

Guinée, J. B., and R. Heijungs. 2011. Life cycle sustainability analysis: Framing questions for approaches. Journal of Industrial Ecology **15**:656-658.

Guinée, J. B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall, and T. Rydberg. 2011. Life cycle assessment: Past, present, and future. Environmental Science and Technology **45**:90-96.

Haines-Young, R., and M. Potschin. 2018. Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure. Available from www.cices.eu. Fabis Consulting Ltd, The Paddocks, Chestnut Lane, Barton in Fabis, Nottingham, NG11 0AE, UK.

Halog, A., and N. Awuah. 2013. The Need for Integrated Life Cycle Sustainability Analysis of Biofuel Supply Chains.

Halog, A., and Y. Manik. 2011. Advancing Integrated Systems Modelling Framework for Life Cycle Sustainability Assessment. Sustainability **3**:469-499.

Honti, G., G. Dörgő, and J. Abonyi. 2019. Review and structural analysis of system dynamics models in sustainability science. Journal of Cleaner Production **240**.

Ioppolo, G., S. Cucurachi, R. Salomone, L. Shi, and T. Yigitcanlar. 2019a. Integrating strategic environmental assessment and material flow accounting: a novel approach for moving towards sustainable urban futures. The International Journal of Life Cycle Assessment **24**:1269-1284.

Ioppolo, G., M. Traverso, and M. Finkbeiner. 2019b. Preface—a new paradigm for life cycle thinking: exploring sustainability in urban development scenarios. International Journal of Life Cycle Assessment.

Kennedy, C. 2012. A mathematical description of urban metabolism. Pages 275-291 Sustainability Science: The Emerging Paradigm and the Urban Environment.

Kennedy, C., J. Cuddihy, and J. Engel-Yan. 2007. The changing metabolism of cities. Journal of Industrial Ecology **11**:43-59.

Kennedy, C., S. Pincetl, and P. Bunje. 2011. The study of urban metabolism and its applications to urban planning and design. Environmental Pollution **159**:1965-1973.

Kennedy, C., I. D. Stewart, N. Ibrahim, A. Facchini, and R. Mele. 2014. Developing a multi-layered indicator set for urban metabolism studies in megacities. Ecological Indicators **47**:7-15.

Kloepffer, W. 2008. Life cycle sustainability assessment of products. The International Journal of Life Cycle Assessment **13**:89-95.

Kronenberg, J. 2016. Nature-based solutions. Pages 241–256 *in* A. Rzeńca, editor. EkoMiasto#Środowisko. Zrównoważony, inteligentny i partycypacyjny rozwój miasta. Wydawnictwo Uniwersytetu Łódzkiego, Wydawnictwo Uniwersytetu Łódzkiego, Łódź (Polska).

Liu, X., S. Ma, J. Tian, N. Jia, and G. Li. 2015. A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO2 emissions: A case study of Beijing. Energy Policy **85**:253-270.

Liu, X., G. Ziv, and B. R. Bakshi. 2018. Ecosystem services in life cycle assessment - Part 2: Adaptations to regional and serviceshed information. Journal of Cleaner Production **197**:772-780.

Loiseau, E., L. Aissani, S. Le Féon, F. Laurent, J. Cerceau, S. Sala, and P. Roux. 2018. Territorial Life Cycle Assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. Journal of Cleaner Production **176**:474-485.

Loiseau, E., G. Junqua, P. Roux, and V. Bellon-Maurel. 2012. Environmental assessment of a territory: An overview of existing tools and methods. Journal of Environmental Management **112**:213-225.

Luederitz, C., E. Brink, F. Gralla, V. Hermelingmeier, M. Meyer, L. Niven, L. Panzer, S. Partelow, A.-L. Rau, R. Sasaki, D. J. Abson, D. J. Lang, C. Wamsler, and H. von Wehrden. 2015. A review of urban ecosystem services: six key challenges for future research. Ecosystem Services **14**:98-112.

Maes, J., and S. Jacobs. 2015. Nature-Based Solutions for Europe's Sustainable Development. Conservation Letters.

Maranghi, S., M. L. Parisi, A. Facchini, A. Rubino, O. Kordas, and R. Basosi. 2020. Integrating urban metabolism and life cycle assessment to analyse urban sustainability. Ecological Indicators **112**.

Marvuglia, A., T. N. Gutiérrez, P. Baustert, and E. Benetto. 2018. Implementation of Agent-Based Models to support Life Cycle Assessment: A review focusing on agriculture and land use. AIMS Agriculture and Food **3**:535.

Marvuglia, A., L. Havinga, O. Heidrich, J. Fonseca, N. Gaitani, and D. Reckien. 2020. Advances and challenges in assessing urban sustainability: an advanced bibliometric review. Renewable and Sustainable Energy Reviews **124**:109788.

Mirabella, N., K. Allacker, and S. Sala. 2018. Current trends and limitations of life cycle assessment applied to the urban scale: critical analysis and review of selected literature. The International Journal of Life Cycle Assessment **24**:1174-1193.

Nassauer, J. I., and P. Opdam. 2008. Design in science: extending the landscape ecology paradigm. Landscape Ecology **23**:633-644.

Offenhuber, D., and C. Ratti. 2014. Decoding the city: urbanism in the age of big data. Birkhäuser, Basel.

Onat, N., M. Kucukvar, A. Halog, and S. Cloutier. 2017. Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives. Sustainability **9**:706.

Onat, N. C., G. Egilmez, and O. Tatari. 2014a. Towards greening the U.S. residential building stock: A system dynamics approach. Building and Environment **78**:68-80.

Onat, N. C., M. Kucukvar, and O. Tatari. 2014b. Towards Life Cycle Sustainability Assessment of Alternative Passenger Vehicles. Sustainability **6**:9305-9342.

Othoniel, B., B. Rugani, R. Heijungs, E. Benetto, and C. Withagen. 2016. Assessment of Life Cycle Impacts on Ecosystem Services: Promise, Problems, and Prospects. Environmental Science & Technology **50**:1077-1092.

Othoniel, B., B. Rugani, R. Heijungs, M. Beyer, M. Machwitz, and P. Post. 2019. An improved life cycle impact assessment principle for assessing the impact of land use on ecosystem services. Science of The Total Environment.

Petit-Boix, A., P. Llorach-Massana, D. Sanjuan-Delmás, J. Sierra-Pérez, E. Vinyes, X. Gabarrell, J. Rieradevall, and E. Sanyé-Mengual. 2017. Application of life cycle thinking towards sustainable cities: A review. Journal of Cleaner Production **166**:939-951.

Pincetl, S. 2012. A living city: Using urban metabolism analysis to view cities as life forms. Pages 3-25 Metropolitan Sustainability: Understanding and Improving the Urban Environment.

Pontee, N., S. Narayan, M. W. Beck, and A. H. Hosking. 2016. Nature-based solutions: Lessons from around the world. Proceedings of the Institution of Civil Engineers: Maritime Engineering **169**:29-36.

Recatalá, L., and D. Sacristán. 2014. A minimum indicator set for assessing resources quality and environmental impacts at planning level in a representative area of the European Mediterranean Region. Ecological Indicators **45**:160-170.

Reed, M. S., A. Graves, N. Dandy, H. Posthumus, K. Hubacek, J. Morris, C. Prell, C. H. Quinn, and L. C. Stringer. 2009. Who's in and why? A typology of

stakeholder analysis methods for natural resource management. Journal of Environmental Management **90**:1933-1949.
Restrepo, J. D. C., and T. Morales-Pinzón. 2018. Urban metabolism and sustainability: Precedents, genesis and research perspectives. Resources, Conservation and Recycling **131**:216-224.
Ruiz-Frau, A., G. Edwards-Jones, and M. J. Kaiser. 2011. Mapping stakeholder values for coastal zone management. Marine Ecology Progress Series **434**:239-249.
Sala, S., B. Ciuffo, and P. Nijkamp. 2015. A systemic framework for sustainability assessment. Ecological Economics **119**:314-325.
Sala, S., F. Farioli, and A. Zamagni. 2013a. Life cycle sustainability assessment in the context of sustainability science progress (part 2). International Journal of Life Cycle Assessment **18**:1686-1697.
Sala, S., F. Farioli, and A. Zamagni. 2013b. Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1. The International Journal of Life Cycle Assessment **18**:1653-1672.
Schaubroeck, T. 2018. Towards a general sustainability assessment of human/industrial and nature-based solutions. Sustainability Science **13**:1185-1191.
Susskind, L., A. E. Camacho, and T. Schenk. 2012. A critical assessment of collaborative adaptive management in practice. Journal of Applied Ecology **49**:47-51.
Vafa-Arani, H., S. Jahani, H. Dashti, J. Heydari, and S. Moazen. 2014. A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. Transportation Research Part D: Transport and Environment **31**:21-36.
Valdivia, S., C. M. L. Ugaya, J. Hildenbrand, M. Traverso, B. Mazijn, and G. Sonnemann. 2013. A UNEP/SETAC approach towards a life cycle sustainability assessment - Our contribution to Rio+20. International Journal of Life Cycle Assessment **18**:1673-1685.
VdE. 2020. Nouveau plan d'aménagement général (PAG) de la Ville d'Esch. Available at: https://administration.esch.lu/nouveau-pag/. Ville d'Esch (VdE), Luxembourg.
Villarroel Walker, R., M. B. Beck, J. W. Hall, R. J. Dawson, and O. Heidrich. 2017. Identifying key technology and policy strategies for sustainable cities: A case study of London. Environmental Development **21**:1-18.
Xing, Y., P. Jones, and I. Donnison. 2017. Characterisation of Nature-Based Solutions for the Built Environment. Sustainability **9**:149.
Zamagni, A., J. Guinée, R. Heijungs, and P. Masoni. 2012. Life Cycle Sustainability Analysis. Pages 453-474.
Zhang, Y., Q. Wu, and B. D. Fath. 2018. Review of spatial analysis of urban carbon metabolism. Ecological Modelling **371**:18-24.
Zhang, Y., Z. Yang, and X. Yu. 2015. Urban Metabolism: A Review of Current Knowledge and Directions for Future Study. Environmental Science and Technology **49**:11247-11263.