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Review

Urban metabolism of the informal city: Probing and measuring the 'unmeasurable' to monitor Sustainable Development Goal 11 indicators

Josephine Kaviti Musango*, Paul Currie, Suzanne Smit, Zora Kovacic

School of Public Leadership, Stellenbosch University, South Africa

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ABSTRACT

African cities rely predominantly on the informal city for their growth, and much of the infrastructure remains within the boundaries of original colonial settlements or cannot keep up with unplanned expansion. Informality is dominant in public transport systems, water and food provision, energy generation and waste removal. Thus, analysing the flows of energy, water, food and waste is a difficult task as they are hard to track and quantify. However, finding ways to assess these flows is an important step to empower urban planners with relevant knowledge about how their cities function. This paper thus explores how urban metabolism can contribute to the assessment of the informal city to monitor progress towards achieving the Sustainable Development Goal 11 indicators. We achieved this through a critical literature review and the use of a case study based on the authors' urban metabolism projects conducted in the African context. The results of the literature review show that urban metabolism research has transitioned from the first wave, namely *intradisciplinary*, to the second wave, *integrated*. Due to the call for inclusive urban metabolism assessments, a a third wave is emerging, *co-designing with communities,* and it promotes situated urban metabolism assessments that engage with local contexts. The case study projects demonstrate the potential to advance informal city metabolism assessments to monitor Sustainable Development Goal 11 indicators, in the *third wave* of urban metabolism research.

1. Introduction

Population growth and urbanisation are central considerations of the sustainable development goals (SDGs), and particularly SDG 11, observed in explicit statements that point to the need to improve urban sustainability and sustainable urbanisation processes. As at mid-2017, the global population was an estimated 7.6 billion people and it is expected to reach 9.8 billion in 2050, to which Africa would contribute more than 50% of the growth (UN-DESA, 2017a).

Growing rates of urbanisation imply that new urban dwellers require access to basic resources such as food, energy and water; basic services such as sanitation, health, education, mobility and information; and basic infrastructures to convey these resource services such as housing, transport systems and power plants. These requirements are currently unmet (Batinge et al., 2017), which poses serious doubts about the viability of satisfying increased future demand. Consequently, academics, community organisations and policy makers are paying more attention to understanding how to shape cities to improve the quality of life of urban dwellers while minimising environmental impacts. Surprisingly, little is known globally about how new urban dwellers in countries of the global South, and more specifically in Africa (Bai et al., 2017), will obtain the increased basic resources and services requirements. Little is also known about the implications of infrastructure development on resource availability, access to services, and environmental impact.

International policy documents such as the SDGs (United Nations, 2016), the New Urban Agenda[1], and Conference of Parties 2015 (COP21)[2], highlight the role of cities in creating sustainable, inclusive and resilient futures (Robin et al., 2017). Further, the diverse issues covered in the SDGs - including poverty, hunger, quality education and healthcare, social and gender equity, and sustainable cities - indicate the urge to improve the lives of marginalised and poor communities. Increasing inequality and social exclusion in urban areas suggests that, to achieve the SDG 11 indicators, we need to move beyond applying technical solutions and expand our understanding of the social, political and cultural context. It also necessitates a better consideration of the urbanisation processes of Africa and Asia, as these two continents are estimated to be the most urbanising.

* Corresponding author.
E-mail addresses: jmusango@sun.ac.za (J. Kaviti Musango), paul.currie@iclei.org (P. Currie).

[1] http://habitat3.org/the-new-urban-agenda/

[2] http://www.cop21paris.org/images/downloads/Sustainable_Cities_by_SIF15.pdf

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Although the SDGs set forth policy targets and frameworks (Hák et al., 2016), much of it requires translation from a national level to regional and local contexts by engaging with city governments. While Robin et al. (2017) indicate that city government across the world tends to lack a basic understanding of existing urban dynamics[3] in their cities, this paper contends that city governments have a better understanding of day-to-day city operations and contextual needs. However, capacity issues limit their ability to deal with increasing urbanisation.

Thus, challenges in implementing and monitoring the SDGs indicators remain acute, specifically for: coordinating local, national and global responses; minimising unintended consequences of responses to goals; and accessing relevant information to understand how to respond, monitor, evaluate and assess progress (Bowen et al., 2017; Hák et al., 2016; Persson et al., 2016). Klopp and Petretta (2017) further identify three key challenges that are specific to SDG 11, namely: (i) poor availability of standardised, open and comparable data; (ii) lack of institutions at the city level to support data collection and monitoring; and (iii) lack of localisation and context specificity. These challenges relate to the fundamental uncertainties of dealing with rapidly changing urban systems, especially concerning informal urbanism, and to the governance challenge of reconciling multiple levels of governance, in which municipal, provincial and national authorities may have overlapping jurisdiction and undefined responsibilities.

Hák et al. (2016) point out that the SDGs will remain ambiguous without scientific support to operationalise the indicators. However, it remains unclear which scientific discipline(s) would inform action, how different perspectives would be combined, and what role non-expert knowledge would play. In addition, the improvement of data is a key aspect for the implementation of the SDGs. As stated in the United Nations report, data needs are crucial for decision makers to fully implement SDGS and to monitor progress; to this end, the data need to be disaggregated, timely, relevant, accessible, accurate and easy to use (UN-DESA, 2017b).

Situated scientific research and evidence that engages with local contexts are therefore crucial to facilitate the measuring, monitoring and evaluating of the SDGs. Such research and evidence require assessments to provide relevant SDG indicators, both quantitative and qualitative indicators, and contributions to local and international urban policy processes and practice (Bai et al., 2017; Bhaduri et al., 2016; World Council on City Data, 2017).

Various urban indicator sets, such as the domestic material consumption per capita previously proposed (e.g. Bandura, 2008; Eurostat, 2007; Tasaki et al., 2010), were operationalised at a national level and lack theoretical consensus on how to measure sustainability (Hák et al., 2016). In addition, the practical application of the urban sustainability indicators and standards[4] has grown significantly. Such applications include: urban sustainability indicators developed by the European Foundation for the Living and Working Conditions (Mega and Pedersen, 1998); sustainable urban development indicators developed by the University of Pennsylvania (Lynch et al., 2011); the North American Green City Index (Economist Intelligence Unit, 2011), which assesses the environmental impact of 27 major US and Canadian cities; eco-city indicators (Joss, 2012); multi-layered indicator sets for urban metabolism (Kennedy et al., 2014); and the Sustainable Cities Index piloted in 30 cities (Arcadis, 2015). Further, Chen and Chen (2014) propose eco-indicators of urban metabolism. Of notable recent advancement is the first international standard for city indicators, namely ISO 37120 (ISO, 2014), developed by the Global City Indicator Facility[5]. While these developments of the urban sustainability indicators and standards are beneficial, a major weakness of the standard is that the indicators push for formalisation and exclude the prevailing informal city in African and Asian cities. According to Guibrunet and Broto (2015), an "informal city" is "an active city that supports multiple aspects of people's lives, but which remains nevertheless invisible to sanctioned structures of urban authority". Hence, standards generate skewed data (Klopp & Petretta, 2017; Kovacic et al., 2019) and knowledge gaps that are blind to the uncertainties omitted bymeasurement. Local knowledge and practices are also filtered out, which result in indicators of little practical applicability in contexts of predominant informality.

For scientific assessments to produce urban sustainability indicators that have a policy and societal relevance and impact in Africa and Asia, scholars need to demonstrate the relevance to bothachieving SDG 11 indicators globally and integrating the existing capabilities and socio-cultural realities of the local context. This paper argues that urban metabolism assessments that *co-design with communities* can support the generation of these relevant SDG 11 indicators for understanding the informal city.

According to Kennedy et al. (2007), urban metabolism is the "sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste". While this is the most cited definition, it is restrictive in the implied methods and practical application of assessment. Further, current urban metabolism assessments do not fully follow the Kennedy et al. definition due to the increased number of elements considered (Cui, 2018). However, their definition provides a foundation for further development. Reshaping this definition, Currie and Musango (2017) define urban metabolism as "a complexity of socio-technical and socio-ecological processes by which flows of materials, energy, people and information shape the city, service the needs of its populace, and impact the surrounding hinterland." This definition calls for integrating both quantitative and qualitative approaches to capture both tangible and intangible aspects that shape the city dynamics. Further, this paper refers to the concept of *co-design with communities* to signal the need to move away from blueprint applications of the SDGs, targets, and indicators, towards engaged urban metabolism assessment practices in which local communities are not just the recipients of ready-made solutions but are part of the design of such solutions.

Therefore, the objective of this paper was to explore how urban metabolism can contribute to the assessment of the informal city to monitor progress towards achieving the SDG 11 indicators. We refer to informal city assessment as an estimation of the human activity and land use in the informal city so as to address socio-economic and urban policy issues that are essential to building sustainable cities and communities. We focused on two research questions to address the objective of this paper. These are: (i) how is urban metabolism research supporting the assessment of the informal city? and (ii) How can informal city metabolism assessments be advanced to monitor the SDG 11 indicators?

The rest of the paper is organised as follows. First, we introduce the concept of urban metabolism and informal city metabolism in Sections 2 and 3 respectively. We then present the methods utilised in Section 4, followed by the results and discussions in Section 5. Finally, we provide conclusions in Section 6.

2. The concept of urban metabolism

The origin of the urban metabolism concept is debated in the literature. According to Lederer and Kral (2015), the concept dates back to 1894, to Theodore Weyl's "Essay on the metabolism of Berlin."

[3] The term urban dynamics as used here refers to the changing movements of people, information and structures in cities, and the forces (including economic, social, political, cultural, and ecological) that shape and reshape cities over time.

[4] We refer standards as standardised measures that are considered universal, yet they tend to shrink contexts that do not reflect these measures.

[5] Refer to Appendix A for a summary of ISO indicators that corresponds to specific SDG targets relevant to cities.

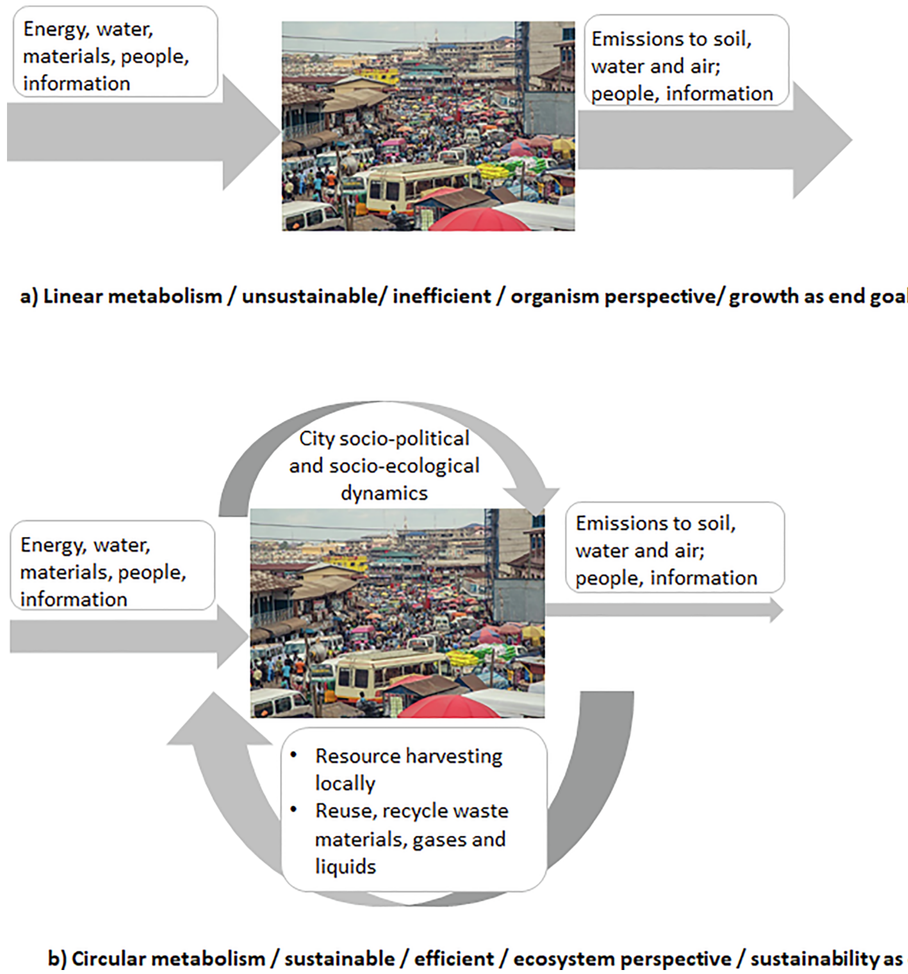

Fig. 1. Growth as end goal versus sustainability as end goal Adapted from Musango et al. (2017).

However, its broader application to understanding and measuring city metabolism is associated with Wolman's (1965) seminal paper of a hypothetical US city constituting a population of one million people.

Golubiewski (2012) analogised urban metabolism as living organisms or ecosystems. The organism metaphor depicts the current configuration of the metabolism of traditional cities, which is mostly linear. Cities rely on their hinterlands for the majority of materials such as biomass, water, building materials, and energy needs (Bai et al., 2017), which are used inefficiently (Agudelo-Vera et al., 2012). Cities dispose of waste generated during consumption in solid, liquid and gaseous forms. Therefore, cities are vulnerable because of their resource dependence on existing linear metabolism, which affects the availability of local resources and degrades the environment through resource extraction and waste disposal. The ecosystem metaphor, in contrast, depicts resource efficiency and closed loops (circular), with all outputs as potential inputs, and offer a stronger outlook for urban sustainability. Recognised as circular metabolism, it resembles a natural ecosystem that consumes efficiently, especially by recycling and reusing resource flows (Doughty and Hammond, 2004), hence reducing reliance on the local hinterland and global trade.

Traditionally, cities' infrastructure has been designed based on linear metabolism (source-consumption-waste) from an orientation of resource abundance. The challenge is to shift to circular metabolism. Urban metabolism assessment is very often used to discuss the balance between cities and ecosystems; because cities need resources, their growth is not independent of the ecosystem's carrying capacity. Therefore, efficiency is a question of compatibility, instead of growth per se. As such, the framework of urban metabolism shifts attention from growth as the end goal to sustainability as the end goal, depicted in Fig. 1. Thus, flow indicators and measures of energy, water, food, waste, and land-use changes (in total and per capita) are obtained from urban metabolism assessments to provide insights into the urban systems (Zhang, 2019). Hence urban metabolism assessment becomes relevant to the field of sustainable development.

The concept of urban metabolism has received traction in relation to how it can provide assessments to support the field of sustainable development, as well as to monitor sustainability indicators and SDGs. Following the Brundtland Report (World Commission on Environment and Development, 1987), it was proposed that urban metabolism, referred to as the 'old concept', should be fused with sustainable development, termed the 'new concept', in order to aid planners[6]. Various studies such as those by Barles (2010), Goonetilleke et al. (2011), Kennedy et al. (2011) and Stimson et al. (1999), denote urban metabolism as a framework and metaphor for investigating quality of life, sustainable urban development issues, and urban planning for sustainable cities. Similarly, the adoption of the 2030 Agenda for SDGs has resulted in proposals for collaboration between urban metabolism and the field of sustainable development (John et al., 2019). While these two fields demonstrate potential for collaboration, what remains unclear is how to move from theory to practice to understand and assess the informal city's metabolism.

[6] White (1990) wrote the manuscript titled, Urban Metabolism and Sustainable Development. A Fusion of Old and New Concepts for Planners. Toronto: University of Toronto. However, the link is currently unavailable and the reference is now found here: http://archive.unu.edu/unupress/unupbooks/80841e/80841E0s.htm

Table 1
Summary of the initial sample of review papers.

Topic from searches	An initial sample of review papers
Urban metabolism reviews	12
Urban metabolism and sustainability reviews	13
Informal settlement metabolism assessment	8

3. The concept of informal city metabolism

To the authors' best knowledge, few studies have defined the concept of informal city. Guibrunet and Broto (2015) definition (refer to Section 1), points to how an informal city remains overlooked in urban planning despite supporting multiple facets of people's lives. Other terms synonymous with informal city, described in Guibrunet and Broto (2015), Smit et al. (2017) and Kovacic et al. (2019), include informal settlements, slums, informal economy, and urban informality.

Informal cities of the global South, and specifically Africa, are observed to exceed formal city structures. The discussion of informal cities is thus widely seen in urbanisation narratives, because urban metabolism studies still focus on formal city assessments utilising conventional quantitative methods such as material flow analysis, ecological footprint analysis, input–output methods, life-cycle assessment, network analysis, emergy assessment (refer to Beloin-Saint-Pierre et al., 2017 and Zhang et al., 2015, for a full list of the conventional methods). A small body of informal city assessments is emerging, which include work by Kovacic et al. (2019), Smit et al. (2019b), Guibrunet et al. (2017), Demaria & Schindler (2016) and Attia & Khalil (2015). These studies utilise unconventional bottom-up methods such as Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) and Community-Based System Dynamics (CBSD) (e.g., Kovacic et al., 2019; Smit et al., 2019a,b) and tools including interviews, surveys, and workshops. Therefore, this paper contributes to this emerging body of knowledge on the alternative understanding and assessments of informal city metabolism to support the monitoring of SDG 11 indicators.

4. Method

This paper utilised a critical literature review to address the first question on how urban metabolism research is supporting the assessment of informal cities to monitor the SDG 11 indicators. Further, we used a case study to address the second question, on how informal city metabolism can be advanced to assess and monitor the SDG 11 indicators. We describe each of these approaches below.

4.1. Critical literature review

We undertook a critical literature review to provide the theoretical development of urban metabolism research and its relevance in assessing informal city to support the monitoring of SDG 11 indicators. The critical review focused on two aspects. The first is that urban metabolism has experienced rapid growth and there are several comprehensive reviews and updates. However, these reviews fail to consider the informal city metabolism in the urbanising world. Secondly, the SDGs, which became effective in January 2016, present the need for new perspectives on how to evaluate, measure and monitor the SDG indicators.

To ensure a comprehensive and exhaustive search process, we utilised a wide range of relevant databases. These include Scopus, Science Direct, and Google Scholar. Scopus provided the most comprehensive list of peer-reviewed articles. As SDGs comprise a new emerging policy-relevant topic, we sourced relevant grey literature and information using Google, as well as specific UN Websites such as the Global Initiative of Resource Efficient Cities (https://resourceefficientcities.org/) and the Sustainable Development Goals platform (https://sustainabledevelopment.un.org/). The searches were done up to June 2019 for all fields, to capture relevant documents. We limited our search to papers in English, and the key terms used were "urban metabolism", "Sustainable Development" and "informal city." Variation was done with synonym terms, such as: 'metabolism', 'sustainability', 'SDGs', 'informal settlement', and "slum'. We used Boolean operators to combine the terms in order to focus the study on informal city metabolism and SDGs.

The selection of the relevant literature was performed on the basis of several integrated criteria: i) identifying papers that have undertaken a review on urban metabolism; ii) containing a topic of interest related to the relevance of urban metabolism in the field of sustainable development; and iii) providing empirical urban metabolism studies that assess and measure the informal city to inform SDGs. We excluded papers on the informal city or informal settlements that do not focus on urban metabolism. Table 1 classifies the number of relevant journals based on the above criteria (see also Supplementary material). Backward and forward searches were then carried out on the sampled review papers to identify further relevant papers based on 'most cited' and 'newest' articles. In addition, we undertook a manual search of grey literature materials from the website of the metabolism of cities publication database[7].

4.2. Case study

We made use of a case study of urban Modelling and Metabolism Assessment Research Team (uMAMA – www.umama-africa.com) projects to demonstrate the potential to advance informal city metabolism to monitor SDG 11 indicators. uMAMA was established in 2015 and uses urban metabolism as a *conceptual framework* and *boundary object*, along with a suite of approaches to estimate data relevant to the monitoring of SDG targets and indicators, and their applicability in the African context. These approaches include:

(i) Development of typologies, such as for the African urban resource typology (Currie, 2015; Currie et al., 2015; Currie & Musango, 2017), slum typology (Makinde et al., 2017; Smit et al., 2017), buildings typology (Muringathuparambil et al., 2017) and household typology (Kovacic et al., 2016);
(ii) Multi-layer indicator set framework (refer to Kennedy et al., 2014) to undertake basic urban metabolism assessments (Currie et al., 2017);
(iii) An adapted Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism developed for application to informal settlements to capture human activities at different scales (Kovacic & Giampietro, 2016; Smit et al., 2019b);
(iv) GIS mapping to spatially visualise infrastructure development;
(v) Case study approaches to gain deeper insights into the complex social phenomena in the informal settlements/slums;
(vi) Bottom-up data collection led by local co-researchers, such as was undertaken in the four informal settlements of Enkanini and Kayamandi in Stellenbosch, South Africa, Mathare in Nairobi, Kenya, and Kasubi-Kawaala in Kampala, Uganda, as well as across household types in Cape Town, South Africa;
(vii) Comparative analysis of case studies, exemplified by the co-designing energy communities with urban poor women (Co-DEC)[8] project (Ambole et al., 2019; Kovacic et al., 2019);
(viii) Visualisation using Sankey diagrams and infographics to reach a wider audience;
(ix) Quantitative storytelling to capture unquantifiable nuances; and

[7] The metabolism of cities database collects papers related to material flow analysis. See the link: https://archive.metabolismofcities.org/publications/list
[8] http://codec.livinglab.co.ke/

(x) System dynamics modelling (Musango, 2018; Musango et al., 2016; Smit et al., 2019a), which would serve as a repository of knowledge that manifests itself in a model to ensure coherence and consistency of information.

We selected the uMAMA case study based on the authors' understanding of the limited number of studies on informal city metabolism assessment, illustrated in Section 3. Further, the existing informal city assessment studies seemed like once-off research. Thus, the development of new projects emanating from the previous project ideas and exploration makes the uMAMA projects case study appropriate to demonstrate the potential to advance informal city metabolism to monitor the SDG 11 indicators in an African context.

5. Results

5.1. Urban metabolism research to support the assessment of the informal city

There are numerous studies that review the concept of urban metabolism (e.g. Zhang, 2019, Beloin-Saint-Pierre et al., 2017; Cui, 2018; Newell & Cousins, 2015; Zhang et al., 2015; Lu & Chen, 2015; Kennedy et al., 2011), propose advancement of urban metabolism perspectives and frameworks (e.g. Dijst et al., 2018; Li & Kwan 2018; Pincetl et al., 2012; Rapoport, 2011), apply the different urban metabolism methods at the city level (e.g. Beloin-Saint-Pierre et al., 2017), examine specific case studies of urban metabolism assessments in various world regions (e.g. Céspedes Restrepo & Morales-Pinzón, 2018; Musango et al., 2017), and demonstrate the linkages of urban metabolism assessments with the sustainability of cities (e.g. Kissinger and Stossel, 2019; Cui, 2018; Conke & Ferreira, 2015; Korpilo, 2014; Kennedy & Hoornweg, 2012; Newman, 1999). As such, the results of this paper do not aim to provide similar reviews, but rather contribute to the discussion of the key evolution of urban metabolism research to facilitate informal city assessment and the monitoring of SDG 11 indicators.

From the review, the urban metabolism research is observed to be transitioning and can be categorised into three waves: (i) first wave: *intradisciplinary*; (ii) second wave: *integrated*; and (iii) third wave: *co-designing with communities* (Fig. 2). We discuss each of these waves on the basis of their contribution to supporting the field of sustainable development, and particularly the SDG targets and the indicators and assessment of informal city metabolism.

5.1.1. First wave: intradisciplinary

During the *intradisciplinary* wave of urban metabolism research developed mainly through the three main intellectual traditions. As described in Newell and Cousins (2015), these traditions are urban ecology, industrial ecology and Marxist ecology. While these three intellectual traditions have matured in their research practices concerning data collection, analysis and discussion, Newell and Cousins (2015) and Wachsmuth (2012) highlight their limitation as their theoretical perspective and urban metabolism assessment methods. Firstly, the metaphors used in the three disciplines have matured; secondly, they have become stagnant and finally, they are rigid in some cases due to the continued use of embedded knowledge and disciplinary concepts (Newell & Cousins, 2015).

Given the differences in the three intellectual traditions and their operation in isolation, the discussions during the *intradisciplinary* wave focused primarily on the conceptualisation of urban metabolism. These discussions include the analogy of urban metabolism as an organism, ecosystem or nature-society interactions as observed in Odum (1971, 1973), and which approaches were the most appropriate for assessing metabolism at the city level. Furthermore, approaches from the field of biology were found to be relevant to investigate and understand the metabolism of cities and its sustainability in general. As such, ecological impacts emanating from human activities are highlighted as a primary driving force of sustainability, as observed in Vitousek et al. (1997).

The discussions observed in the *intradisciplinary* wave indicate the relevance of sustainability issues even in the very early stages of urban metabolism research. However, the city level empirical assessments of urban metabolism utilise national-level data that is mostly limited to cities in the global North as illustrated in Brunner et al. (1994), Newcombe et al. (1978) and Newman (1999). Despite the efforts at city-level urban metabolism assessment, the main challenges that limited the contribution to sustainable development during this period include a lack of standardised city-level assessment approaches, methods and indicators, and the absence of city-level data in all cities, and more severely, in the cities of the global South (Currie and Musango, 2017; Kennedy et al., 2007).

5.1.2. Second wave: integrated

The *integrated* wave of urban metabolism research is characterised by a conception of urban metabolism that not only illuminates the various aspects of urban sustainability but also encourages dialogue in disconnected intellectual disciplines. Based on the reviewed literature, we envisage that the *integrated* wave emerged almost a decade after the World Commission on Environment and Development coined the term sustainable development. In addition, the mainstreaming of sustainable development strengthened the need for collaboration between the three main intellectual traditions and other fields. As the intellectual traditions of urban metabolism embarked on efforts to contribute to sustainable urban development, it became clear that there is a need to focus beyond environmental considerations and should include an understanding of the socio-economic, socio-technical and socio-political processes that shape city metabolism (Zimmer, 2010).

The studies observed in the *integrated* wave focus on interdisciplinary research, as highlighted in Chrysoulakis et al. (2013) and Broto et al. (2012), and leverage disciplinary strengths to tackle the major disciplinary challenges. Further, prominent scholars in the traditional disciplines such as Mitchell (1998), Brunner (2007) and Kennedy et al. (2010) advocate the integration of social, health and economic indicators into the framework of urban metabolism. In addition, efforts to operationalise urban metabolism at the city level are demonstrated by the Global Initiative for Resource Efficient Cities (GI-REC)[9] of the United Nations Environmental Programme and the Global City Indicator Facility[10], which led to the development of the first ISO recognised city indicators, ISO 37120.

A prominent aspect of the *integrated* wave is the interest of scholars in disciplines beyond the three intellectual traditions of urban metabolism. These include scholars in disciplines such as geography (e.g. Heynen et al., 2013; Newell & Cousins, 2015), sustainable development (e.g. Currie & Musango, 2017) and urban planning (e.g. Farzinmoghadam, 2016). Therefore, urban metabolism is on the frontier of the academic bridge, and terms such as *Urban Metabolism 2.0* (Pincetl et al., 2012) and *Political-Industrial Ecology* (Newell & Cousins, 2015) can be associated with the *integrated* wave. According to Newell et al. (2017), political-industrial ecology focuses on "how resources (materials and energy) flows and stocks can shape and become shaped by the environmental, socio-economic and political processes and patterns over time and space". Proponents of political-industrial ecology argue that it can address the shortcomings of political ecology, namely, social at the expense of ecological, methodological cityism, and the prevalence of qualitative approaches (Newell & Cousins, 2015). This argument shows the need for theories and methods of urban metabolism to explore cities differently, especially when probing the informal city metabolism of rapidly urbanising cities of the global South.

Recognising that urbanisation is a social process and that energy and material exchanges are highly political, the perspective of political-

[9] https://resourceefficientcities.org/

[10] http://www.citiesalliance.org/node/2529

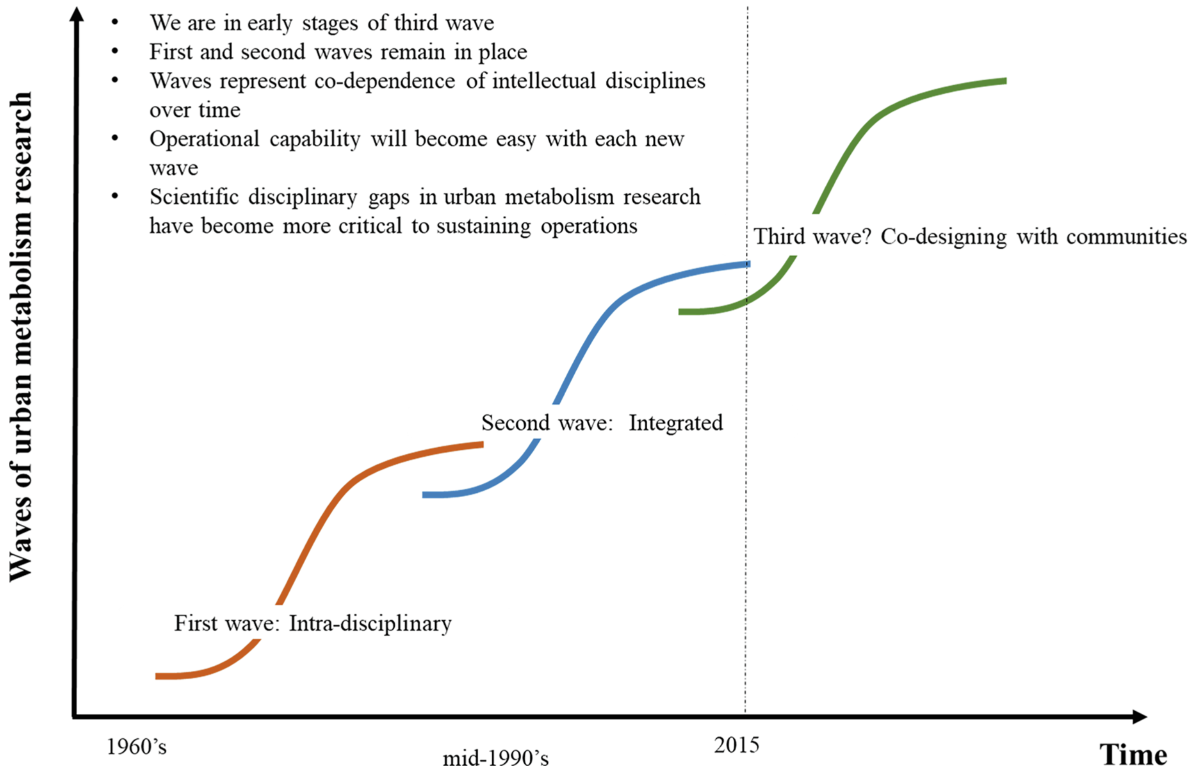

Fig. 2. Waves of urban metabolism research *Source: Authors.*

industrial ecology resonates with the observed realities of the contexts of the global South, where resource inequities are often widespread and visible. The main research gap in the *integrated* wave is the limited inclusion of the informal city in urban metabolism studies, as only a limited number of such studies exist, as illustrated by Attia and Khalil (2015), Guibrunet et al. (2017) and Smit et al. (2019b). To address the research gap in the integrated wave, we found it necessary to accelerate empirical case studies to support urban planning in the global South. This can be through extending assessments beyond the conventional quantitative methods, such as material flow analysis, life cycle analysis and ecological footprint analysis, which require massive amounts of detailed quantitative data.

It remains a challenge to undertake the conventional quantitative assessments in data-scarce environments. Furthermore, it is possible to develop standardised but situated approaches that engage with local communities, based on political-industrial ecology, in order to incorporate the informal city in urban metabolism assessments, and to provide a realistic, holistic understanding of the city. Moreover, it is crucial to consistently communicate the relevance and applicability of urban metabolism approaches in policy, practice and society (Renouf et al., 2017) so as to support the assessment of informal city metabolism.

5.1.3. Third wave? Co-designing with communities

Given the research gaps that persist in the *integrated* wave, a third wave of urban metabolism research, namely *co-designing with communities*, is emerging to promote and contribute to SDGs, targets, and indicators. Further, the *co-designing with communities integrated* wave calls for the assessment of informal city metabolism in the rapidly urbanising cities of the global South.

It is noteworthy that the SDGs, which came into effect in 2016, necessitate the support to co-design with communities. This is similar to what has been observerd in the field of science studies by scholars such as Collins and Evans (2002), Nowotny (2003) and Jasanoff (2004) observed. They call for and have identified a third wave of scientific practices that: (i) takes into account the blurred boundaries between experts and non-experts (Collins and Evans, 2002); (ii) argues for the production of socially robust knowledge (Nowotny, 2003); and (iii) analyses scientific knowledge as the output of a process of co-production between technological and social orders (Jasanoff, 2004). With the new and enhanced role of knowledge co-production practices in sustainable development, Bai et al. (2017) and Teferi and Newman (2017) provide evidence that urban metabolism is useful and relevant for understanding metabolism and sustainability in rapidly urbanising contexts. In addition, Dijst et al. (2018) present a White Paper advocating for urban metabolism to address sustainability transitions. The need for sustainability transition is evident in policy arenas such as those sorrounding SDG 11, which recognise the building of sustainable cities and communities; the Paris Agreement endorsed during COP21 in December 2015, in which cities were posited as central to the challenge of climate change; and the New Urban Agenda, approved at Habitat III in October 2016, which represent the first UN document to state the important role of sub-national governments in tackling global issues.

While the *integrated* wave of urban metabolism research describes the transition beyond the three intellectual traditions, the *co-designing with communities* wave aims to push the concept's boundaries to permeate practice through the involvement of local communities, and for it thus to make concrete contributions to the SDG indicators, rather than to blueprint solutions and the proliferation of standards. Emerging studies have highlighted the shift from urban metabolism theories to their practice. This shift can be effected through several approaches including integrative and systems approaches (Bai et al., 2017), systems thinking (Teferi and Newman, 2017), transdisciplinary research and system dynamics modelling (Musango et al., 2017), and the co-production of knowledge with stakeholders, as highlighted in Bai et al. (2017), Musango et al. (2017), and Teferi and Newman (2017). In addition, Lang et al. (2012) and Webb et al. (2018) point to the crucial role of co-design and co-production of knowledge to support policy- and decision-makers in order to understand and manage progress towards achieving the SDGs. This is because the involvement of the community in research design ensures that the results of the research are more suitable for implementation or inclusion in policy processes and that we identify the community needs explicitly.

The ISO 37120 and the World Council on City Data focus on the measurement of city services and quality of life (World Council on City Data, 2017). They include quantitative, qualitative or descriptive sets of measures and metrics that provide a globally standardised set of definitions and methods. However, the currently proposed indicators exclude several qualitative and quantitative indicators that are relevant to the global South. Empirical urban metabolism assessment case studies, especially of African cities, are essential to facilitate monitoring of the progress with SDG indicators, and to co-design implementation with different stakeholders, including policy and decision-makers, and communities affected by the interventions.

5.2. Advancing informal city metabolism assessments to monitor SDG 11 indicators in the third wave

The SDGs represent a policy framework that requires a holistic approach to urban solutions rather than sector-specific responsibilities (Teferi and Newman, 2017). Similarly, SDG 11 acknowledges that urban problems are integrated with other SDGs, requiring the need for integrated approaches (Teferi and Newman, 2017). Thus, to incorporate SDG 11 with other SDGs, systems thinking and system dynamics approaches are required to provide better outcomes for a range of goals, targets and indicators (Teferi and Newman, 2017). As an example, upgrading informal settlements is not simply about the provision of housing and infrastructure in terms of the number of houses or sanitation services, but also includes prioritising informal economic, social and community activities that take place within these spaces. Thus, to address these issues in the informal city effectively, a systems perspective is a requirement.

As a process towards advancing informal city metabolism assessment, Table 2 illustrates how each SDG 11 target, links with other sustainable development goals. Furthermore, the relevant contribution from urban metabolism assessment, using both conventional and unconventional methods (not mainstreamed) is proposed and presented in Table 2. For example, in Target 11.1, the aspects for assessment are 'housing', 'basic services' and 'upgrade slum'. This target can be related to SDGs 2, 3, 4, 6, 7, 9, 12 and 14 dealing with the components of food, wellbeing, education, water, energy, innovation, responsible consumption and production, and life below water, respectively. As emphasised in Petit-Boix et al. (2017), these linkages indicate the many facets that exist to characterise a sustainable city, ranging from buildings, energy, food, green spaces and landscapes, mobility, urban planning, water and waste. The conventional urban metabolism assessments, such as material flow analysis, can be utilised to track the flow of energy, food and water resources in order to support the measurement of access to basic services. However, in the informal city, unconventional approaches such as an adapted MuSIASEM, piloted by authors in four informal settlements, can be appropriate for the assessment of informal city metabolism, as illustrated in Kovacic et al. (2019) and Smit et al. (2019a,b). Similarly, undertaking slum typology assessment, following the typology framework developed in Smit et al. (2017) can provide a better understanding of the target for upgrading slums.

To further demonstrate how urban metabolism assessment can contribute to the *co-designing with communities* wave, Appendix A presents the assessment of specific SDG targets and the respective ISO 37120 indicators. The efforts to link SDG targets to existing ISO standards, abstracts from local communities and ideas of co-design, which leads to the following two questions: (i) is there tension between international targets such as the SDGs and the co-design wave of urban metabolism? and (ii) is there a tension between the definition of international standards like ISO 37120 and the situated bottom-up approach proposed? This paper argues that SDGs and ISO 37120 indicators offer useful guidelines, but may not be directly applicable in the urbanising contexts of Asia and Africa. Therefore, in the *co-designing with communities* wave, targets and standards need to be adapted when scaled down to local contexts. In addition, standards are generally modelled based on contexts of the global North and could be revised and benchmarked to case studies from the global South, the informal city as well as the formal city.

5.3. Towards empirical relevance of informal city metabolism: the case of uMAMA projects

The approach to urban metabolism assessments can help to fill data gaps in national statistics by understanding urban processes and their associated flows as a means of inferring data using typologies and scaling methods. We demonstrate the potential to fill the data gap using the first uMAMA project, Africa Urban Resource Typology[11]. The project used national resource data and urban scaling methods (refer to Bettencourt et al., 2007), to develop the first ever African resource profiles of 120 African urban areas. The project results showed 10 city groups clustered by per-capita resource intensity, and 11 city groups clustered by resource consumption per unit of GDP. The clusters allowed for resource efficiency and resource intensity and a comparison between the different African cities, hence supporting the benchmarking of comparable cities (see Fig. 3). The outputs from the Africa Urban Resource Typology project contribute to a more situated understanding of how SDG 8, indicator 8.4.2 and SDG 12, indicator 12.2.2 may be scaled down to the level of the city while taking into account the diversity of case studies (refer to Table 3).

As Africa urbanises, it becomes crucial to expand infrastructure to increase access to resources and services while reducing resource flows (resource efficiency). However, the Africa Urban Resource Typology project failed to investigate urban infrastructures that convey resources to different end-users and the political dynamics in each city that we recognise as essential determinants of resource consumption. In addition, the per capita estimate takes into account the population with unmet energy and material requirements, which makes the countries with large populations appear resource efficient.

Therefore, it is useful to assess flows with regard to their processes. Despite these challenges, the Africa Urban Resource Typology project provides baseline material and energy flow indicators for 120 urban areas in Africa, an important first step to advance urban metabolism assessments. The project also advocated for concerted efforts to collect city-level data, along with bottom-up approaches to enable the validation of nationally scaled analysis. Furthermore, typologies allow for situated quantification, unlike the generic "economic agent", "household" or "city", which relies on averages and large statistical databases, and becomes problematic when adapting the knowledge created to specific contexts such as in African cities. With typologies, we undertake "careful quantification" in that we acknowledge that our quantification is not universally valid. Still, we produce knowledge that reflects African and informal reality, and we do not require huge databases but can work with smaller samples (e.g. 100 households).

Although the resource profiles typology project was not initially planned in the context of the research relating to the *co-designing with the communities* wave, the challenges of data collection, the realisation of the diversity of African cities and the vibrant socio-economic aspects necessitated a shift to engage with the local stakeholders. Thus, the project researchers embarked on research visits to six selected case cities – Cairo, Kinshasa, Luanda, Nairobi, Lagos and Cape Town - and the project culminated in *resources and urban Africa workshop* that brought together the stakeholders identified in these six case studies. The Africa

[11] See http://www.umama-africa.com/projects/index.html

Table 2
Linkages of SDG 11 targets with other sustainable development goals, and relevant contribution from urban metabolism assessment.

SDG 11 target (aspects of consideration in italics)	Description of SDG 11 targets linkages with other SDGs and proposed urban metabolism assessment in italics
11.1 Ensure access for all to adequate, safe and affordable *housing* and *basic services* and *upgrade slums*	● Affordable *Housing* will require being innovative and building infrastructure (SDG 9), which have a local context and promote responsible consumption and production (SDG 12). - *Material flows analysis for housing requirements* ● Access to basic resources – Food (SDG 2 and SDG 14); Water (SDG 6) and Energy (SDG 7); Access to basic services – Health (SDG 3); Education (SDG 4); and Sanitation (SDG 6). - *Resource flows analysis and/or resource consumption profiles of food, water, energy and population dynamics* - *Slum typology assessment* - *Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)* - *Participatory infrastructure mapping*
11.2 Provide access to safe, affordable, accessible and sustainable *transport* systems for all	● Sustainable Transport is complex and requires integrated planning and partnerships (SDG 17) and Innovation (SDG 9) and is linked to Energy use (SDG 7); Climate Action (SDG 13); Mobility of people to access decent work (SDG 8). - *Urban mobility flows*
11.3 Enhance *inclusive* and *sustainable urbanisation* and capacity for participatory, integrated and sustainable human settlement planning and management	● *Inclusive* and *sustainable urbanisation* requires strong partnership at all levels and co-designing with the communities. - *Co-designing and transdisciplinary approach*
11.4 Strengthen efforts to protect and safeguard the world's *cultural* and *natural heritage*	● Protecting world cultural and natural heritage requires partnerships (SDG 17) and is linked to resource management in SDG 15 - *Cultural value also implies valuing local knowledge, hence requiring co-designing and transdisciplinary approach*
11.5 Significantly reduce deaths, people affected and direct economic losses caused by *disasters*, with a focus on protecting the *poor and people in vulnerable situations*	● Reducing losses caused by disasters is linked to SDG 1 and encouraging economic growth (SDG 8). - *Money flows and increasing urban resilience by taking into account the urban informal economy, adapted to vulnerable people*
11.6 Reduce the adverse per capita *environmental impact* of cities, including by paying special attention to air quality and municipal and other *waste management*	● Reducing the *environmental impact* of cities relates to responsible consumption and production (SDG 12). - *Waste flows and/or waste profiles*
11.7 Provide universal access to safe, inclusive and accessible *green* and *public spaces* for all	● Green and public spaces are linked to good health and wellbeing (SDG 3); reducing inequality (SDG 10). - *Green spaces may increase gentrification; hence, co-designing and transdisciplinary approach are necessary to ensure that interventions benefit the poor and not just the rich*
11a Support positive economic, social and environmental *links between urban, peri-urban and rural* areas	- Linking urban, peri-urban and rural areas aims to promote decent work and economic growth in all areas (SDG 8); reduce inequality (SDG 10); promote responsible production and consumption (SDG 12). This will require strong institutions at all levels (SDG 16) and partnerships (SDG 17).
11b Substantially *increase the number of cities and human settlements* adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels	● An increasing number of cities and human settlements will require an understanding of population dynamics and resource requirements in order to promote sustainable production and consumption (SDG 12), climate action (SDG 13) and life on land (SDG 15).
11c Support least developed countries, including through *financial and technical assistance*, in building sustainable and resilient buildings utilizing local materials	● Financial and technical assistance implies building strong institutions (SDG 16) and enhancing partnerships at all levels (SDG 17). - *Establishment of City Observatories to facilitate city-level bottom-up data collection at regular intervals (e.g. every three years)*

Urban Resource Typology project formed the basis for our future urban metabolism research, which aims to validate, challenge and complement conventional approaches through co-design with communities and exploring unconventional methods.

It may seem radical to break away from the practice of the three main intellectual traditions, but it is a robust approach to substantially aid the probing of the unmeasurable – informal city metabolisms – in order to contribute to monitoring the progress towards the SDG 11 indicators. The probing of the unmeasurable includes undertaking purpose-driven data collection, as highlighted in Pincetl and Newell (2017), especially through bottom-up approaches. Often, data availability is a challenge in the first and second waves. However, Culwick et al. (2017) question 'how can we do more with less [data]?' Much of traditional data collection occurs at the national level by statistical agencies (Klopp and Petretta, 2017). However, new approaches to data collection are essential at more frequent intervals because the data from informal urban settlements is dynamic and changes rapidly. As an example, in one informal settlement where the uMAMA team collected data, the population almost doubled in three years. Such an observation emphasises the need to collect informal city data regularly, possibly by establishing city observatories such as the Gauteng City-Region Observatory (GCRO)[12], in South Africa. Since its formation in 2008, GCRO has collected quality of life data for the Gauteng region every three years. In the dynamic and rapidly changing urban areas in Africa, it is no longer appropriate to wait for decennial census data. In addition, the observatory would be led by researchers who carry out relevant policy research, resulting in more useful data.

The data collection process matters. When dealing with the informal city, the question is usually, where do you start? Based on experiences in the uMAMA projects, working with community members as co-researchers facilitates a better understanding of the form, function and experiences of informal city, particularly as observed and voiced by informal settlement residents and other stakeholders. Furthermore, asking similar generic questions (e.g. what is the typology of slum X, Y or Z, based on the Smit et al., 2017 framework), allows for

[12] http://www.gcro.ac.za/

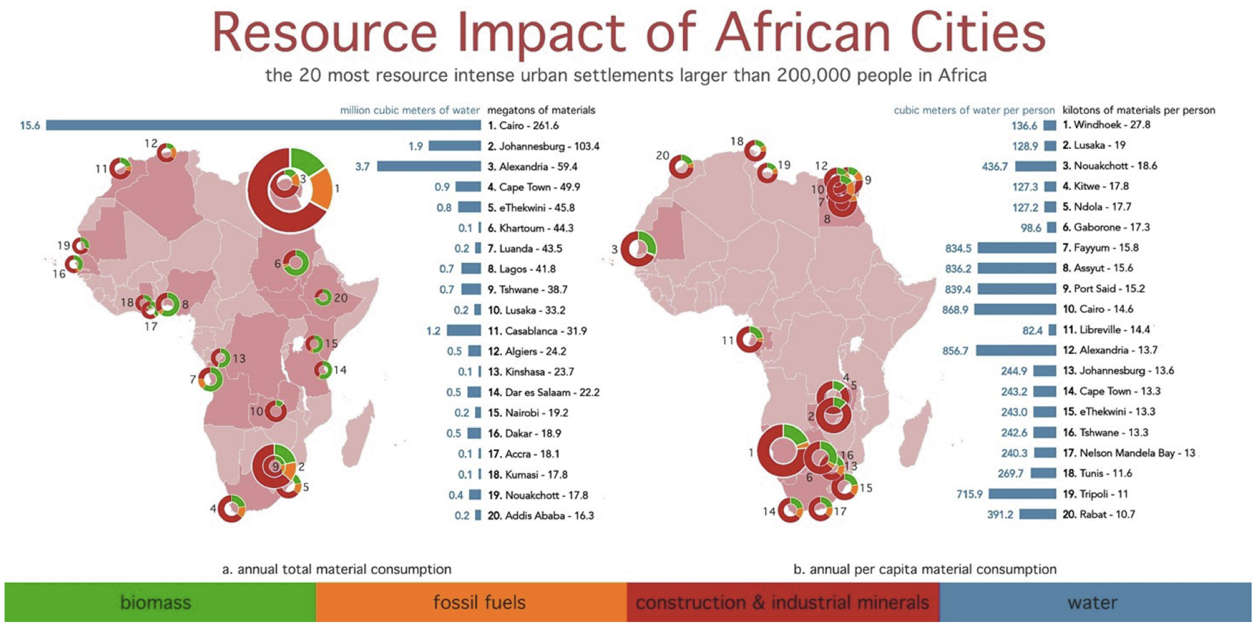

Fig. 3. The top 20 resource intense African cities Source: Currie and Musango (2017).

Table 3
Contribution of the African urban resource typology project to the sustainable development goals.

SDG and Target	Indicator	Project output contribution
SDG 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all *Target 8.4*: Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation	8.4.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP	Estimating DMC at the urban scale is quite challenging and might not be of relevance to the urban decision-makers and policy makers. Total material and energy consumption, total material and energy per capita, and total material and energy consumption per GDP thus were estimated for 120 African urban areas and contribute to SDG 8, indicator 8.4.2 and SDG 12, indicator 12.2.2
SDG12: Ensure sustainable consumption and production patterns *Target 12.2*: Achieve by 2030, sustainable management and efficient use of natural resources	12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP	

benchmarking. The experiences and reflections related to three additional uMAMA projects demonstrate this observation. These projects are the Societal Metabolism of Urban Informal Settlements; Co-designing Energy Communities with Urban Poor Women with cases in Kenya, Uganda and South Africa; and Differential Urban Metabolism in the City of Cape Town. These three projects were designed specifically within the context of co-designing with communities, in which multiple levels of internal and external actors are recognised. For example, a resident researcher in Africa, researching an informal settlement in Africa, may be considered *internal*, compared to a researcher from outside the continent, who is considered as *external*. The researcher in Africa, on the other hand, may be regarded as *external* to the informal settlement if he or she does not live in that area. Being inside the situation provides personal and lived experiences. However, internal actors can be biased in their lived experiences or take certain system functions for granted.

In contrast, the external actor may question observed functions or issues – which can be done through probing or poking. Probing occurs when we diligently and consistently undertake research to provide long-term societal and policy solutions. In contrast, poking is a once-off analysis that omits aspects of the lived experiences and focuses mainly on external theory to interpret the data collected. Therefore, the *co-designing with communities* wave of urban metabolism requires empirical and theoretical research agendas driven by local researchers with support from external theorists. The *co-designing with communities* wave can enhance triple loop learning, in which we understand more about informal city metabolism and how to shape its future assessment methods, and the learnings produced in the learning about the dynamics and assessments of informal city metabolism.

The use of co-designed unconventional integrative methods such as quantitative storytelling developed in Saltelli and Giampietro (2017) and based on MuSIASEM, can guide in describing the informal city's human activities. Therefore, the size and structure of human activities are essential for the development of urban metabolism research. MuSIASEM captures these interrelations between human activity, the consumption of resources and contribution to the economy, making it possible to assess the sustainability of human society (Kovacic et al., 2016; Smit et al., 2017; Wang et al., 2017). We piloted a co-designed MuSIASEM in four informal settlements, and a template questionnaire that is available in Kovacic et al. (2019) can be customised for other informal settlements and for other resource flows such as water, waste and people, for benchmarking and comparison.

In the Societal Metabolism of Urban Informal Settlements project, Smit et al. (2019b) show how informal city quantification informs the theory and practice of urban metabolism assessments and its implications to policy and society. Such assessments allow a transition from the quantification of flows to understanding the processes (Giampietro and Mayumi, 2000; Giampietro et al., 2011) and intangibles that influence these flows (Bai et al., 2017; Dijst et al., 2018; Petit-Boix et al., 2017). For example, Smit et al. (2019a) identified issues like legitimacy, representation and Ubuntu as essential for shaping the political economy dynamics of informal city resource flows. It is often possible to overlook these insights if a project refrains from co-designing with local communities. In addition, the relevant indicators obtained from the Societal

Table 4
Contibution of the societal metabolism of informal settlement project to the sustainable development goals, targets and indicators in the Enkanini case study.

SDG and target	Indicator	Project output contribution
SDG 1: End poverty in all its forms everywhere *Target 1.4* By 2030, ensure that all men and women, in particular poor and vulnerable, have equal rights to economic resources as well as access to basic services, ownership and control over land and other forms of inheritance, natural resources and appropriate new technology and financial services including microfinance *arget 1a* Ensure significant mobilisation of resources from a variety of sources	1.4.1 Proportion of population living in households with access to basic services 1.4.2 Proportion of total adult population with secure tenure rights to land, with legally recognised documentation and who perceive their rights to land as secure, by sex and by type of tenure 1.a.1 Proportion of resources allocated by the government directly to poverty reduction programmes 1.a.2 Proportion of total government spending on essential services (education, health and social protection)	Mapping infrastructure to identify access to resources in the informal settlements. There has been limited to no government spending in Enkanini to provide essential services, despite the population contributing to the economy of Stellenbosch Municipality Identifying the informal settlement typology allows for an indication of land control and tenure rights. No households have land tenure in Enkanini
SDG 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture *Target 2.4* By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	2.4.1. Proportion of agricultural land under productive and sustainable agriculture	Mapping land use change provides insights into the available land for agricultural production. With the Enkanini population growing rapidly, the expected available land will decrease over time
SDG 3: Ensure healthy lives and promote well-being for all at all ages *Target 3.8* Achieve universal health coverage, including financial risk protection, access to quality essential health-care services and access to safe, effective, quality and affordable essential medicines and vaccines for all.	3.8.1 Coverage of essential health services	Mapping infrastructure and livelihood activities identify the availability of health services infrastructure. In Enkanini, there was no health services related infrastructure Community-based system dynamics modelling workshop highlighted health effects ofdifferent energy fuel sources
SDG 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all *Target 4a* Build and upgrade education facilities that are child, disability and gender sensitive and provide safe, non-violent, inclusive and effective learning environments for all.	4.a.1 Proportion of schools with access to: (a) electricity; (b) internet; (c) computers …	Mapping infrastructure and livelihoods activities identify the availability of education facilities. At the time of stuey, there were three informal day care services, run by community members. No basic education infrastructure in Enkanini and some of the residents rely on the primary school in the neighbouring informal settlement. Human activity data indicates that Enkanini children have to travel almost two hours per day to get to schools, situated in neighbouring towns.
SDG 6: Ensure availability and sustainable management of water and sanitation for all *Target 6.1* By 2030, achieve universal and equitable access to safe and affordable drinking water for all		Mapping infrastructure and livelihoods activities identified the limited and inadequate availability of water and sanitation. The houses do not have sanitation and residents only make use of public toilet blocks
SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all *Target 7.1* By 2030, achieve universal access to affordable, reliable and modern energy services *Target 7.2* By 2030, increase substantially the share of renewable energy in the global energy mix	7.1.1 Proportion of population with access to electricity 7.1.2 Proportion of population with primary reliance on clean fuels and technology 7.2.1 Renewable energy share in the total final energy consumption	By mapping infrastructure and utilising MuSIASEM in Enkanini, we identified the proportion of the population with access to electricity as well as the fuel mix per household ranging from solar PV to traditional fuels.
SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable *Target 11.1* By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums *Target 11.3* By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries *Target 11.6* By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.1.1 Proportion of urban population living in slums, informal settlements or inadequate housing 11.3.1 Ratio of land consumption rate to population growth 11.6.1 Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities	All residents in Enkanini live in shacks; although a number of them, live in an improved shack (iShack), which has better aesthetics relative to the normal shack. Enumeration of the Enkanini informal settlement contributes to measuring the proportion of Stellenbosch town residents who live in slums. As the Enkanini population increases, the land available is increasing at a slow rate, given the landscape of the area, which is not demarcated as a residential area. Mapping of Enkanini indicates a lack of formal waste removal.

Metabolism of Urban Informal Settlements project include: (i) the proportion of the population employed and the type of employment, which are relevant to Target 1a, indicator 1.a.2; (ii) fuel consumption per household type, which informs the SDG7 Target on the access to modern energy; (iii) the number of households with electricity connections; and (iv) tipping points for energy fuel switching (see Table 4).

More empirical case studies from the global South, especially Africa, can enable peer-to-peer urban benchmarking and a deeper understanding of the diversity exhibited in informal city metabolism. In addition, we recognise the need to move away from the collectivisation of the entire city (typically undertaken for global benchmarking and reliant on top-down approaches) to differential urban metabolism which explicitly explain the spatio-temporal realities of cities. As emphasised in Thomson and Newman (2017), this is more practical for decision-makers because such an approach can help to examine different parts of the city in detail or to aggregate back to city-level as part of a process of reconciliation.

6. Conclusion

Building sustainable cities and communities as set out in SDG 11, is not a straightforward issue. While scientific research is required to support and operationalise the targets and indicators, it is crucial to consider the role of communities and the political, social and cultural contexts in which the SDGs are applied. One key challenge is how to measure the diverse characteristics of cities in the global South, dominated by the informal city, to monitor their sustainability progress.

Therefore, this paper explored how the concept of urban metabolism can contribute to informal city assessments to inform the SDG 11 indicators. From the critical literature review, the paper shows that urban metabolism research has manifestations from the first wave: *intradisciplinary* research, and the second wave: *integrated* research, to the third wave: *co-designing with communities*. The concept of *co-design with communities* in the third wave signals the need to incorporate local knowledge and practices in order to derive indicators that are applicable in contexts of predominant informality. Such an approach results in a deeper understanding by the actors involved and improves indicator development and ownership of the initiatives to monitor, evaluate and track the SDG 11 indicators.

The case study projects in urban metabolism research demonstrate the possibilities of advancing informal city metabolism assessments by engaging with the experiences of internal actors and external theorists. It is not an easy process. However, the need to undertake research that has societal and policy relevance is indispensable, particularly in order to support the achievement of the 2030 Agenda for sustainable development. Therefore, to advance the assesement of informal city metabolism to monitor the achievement of the SDG 11 indicators, future urban metabolism research to has to co-design with communities to provide empirical assessments that are relevant, along with practical, context specific indicators.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A: Linking contributions from urban metabolism research in the third wave with SDG targets and ISO 37120 indicators

SDGs	Contributions from urban metabolism research in the 3rd wave	ISO 37120 indicators
SDG1: No poverty UN target 1.4: Poor and vulnerable have access to services, economic resources and control over land UN target 1.5: Resilience to exposure and vulnerability to climate related extreme, economic and social disasters UN target 1a: Mobilisation of resources from various sources UN target 1b: Creating sound policy frameworks	Mapping location of slums Slum typology Slum case study Population dynamics Land dynamics Money flows Mapping infrastructure and human activities	ISO 37120 indicator 15.1: % of city population living in slums ISO 37120 indicator 15.3: % of households without registered legal title ISO 37120 indicator 5.5: youth unemployment ISO 37120 indicator 21.1: % population with potable water ISO 37120 indicator 21.3:% city population with access to improved sanitation ISO 37120 indicator 7.2: % of population with authorised electrical service ISO 37120 indicator 16.1: % of population with regular waste collection ISO 37120 indicator 20.1: % serviced with waste water collection ISO 37120 indicator 10.3: number of deaths from socio-economic disasters – e.g. shack fires ISO 37120 profile indicator: gross capital budget ISO 37120 indicator 9.3: own source revenue as % of total revenue
SDG2: Zero hunger	Food flows Household food dynamics	
SDG3: Good health and wellbeing Reduce number of deaths from water contamination	Mapping infrastructure and human activities Workforce skills mapping	ISO 37120 indicator 21.1: % population with potable water
SDG 4: Quality education	Infrastructure mapping Population dynamics do identify school going population	Education ISO 37120 indicator 6.6% of school aged population enrolled in school ISO 37120 indicator 6.2% of students completing primary education ISO 37120 indicator 6.3% of students completing secondary education ISO 37120 indicator 6.4 primary education teacher -student ratio ISO 37120 indicator 6.5% of school-aged population enrolled in schools

SDG 5: Gender equality	Human activity and time use data at the individual and household level indicate gendered aspects of participation in maintaining the household, employment, income generation, energy use and education	ISO 37120 indicator 6.5% of female school-aged population enrolled in schools
SDG 6: Clean water and sanitation UN target 6.1: Universal and equitable access to affordable and clean water	Water flows Waste water flows Mapping infrastructures Household water dynamics and water services	Waste water Water and sanitation ISO 37120 indicator 21.1: % population with potable water ISO 37120 indicator 21.4: total domestic water consumption ISO 37120 indicator 21.6: average annual hours of water service interruption per household
SDG 7: Affordable and clean energy UN target 7.1 Universal access to affordable, reliable and modern energy services UN target 7.2 Increase share of renewable energy UN target 7.3 Improvement in energy efficiency UN target 7a: Financing energy infrastructure UN target 7b: Investment in energy infrastructure	Energy flows Mapping energy infrastructure Mapping social dynamics and perceptions of fuel/ energy type Energy consumption by building type Mapping energy access dynamics Mapping sufficiency of energy sources	Energy Proportion of population with authorised electricity access Percentage of total energy derived from renewable sources Energy consumption by building type Energy use per capita
SDG 8: Decent work and economic growth UN target 8.1: Sustain per capita economic growth UN target 8.2: Economic growth, high innovation UN target 8.5: Full and productive employment and decent UN target 8.6: Reduce the number of youth not in employment	Allocation of hours of human activity at individual level to different compartments that express the key functions performed by the settlement to operate and reproduce itself as related to the household sector and paid work sector Capturing of informal and formal work contributions to primary, productive and services and government sectors Capturing informal and unpaid work activities	City human activity per capita (for informal settlement, you identify if it is consumptive or productive) Percentage of persons in full-time employment
SDG 9: Industry, innovation and infrastructure		Telecommunications and innovation
SDG 10: Reduced inequality UN target 10.1: Achieve and sustain income growth of bottom 40% at a rate higher than national average UN target 10.2: Empower and promote the social, economic and political inclusion of all UN target 10.7: Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies	Mapping human activity in informal settlements to understand the dynamics Mapping population dynamics Mapping money flows Mapping income and expenditure flows/ dynamics	Type of informal settlement Household composition ISO 37120 profile indicator: income distribution – gini coefficient is not a best measure Dwelling type in the informal settlements
SDG 11 Sustainable cities and communities UN target 11.1: Access for all to adequate, safe and affordable housing and basic services and upgrade slums UN target 11.2: Access to safe, affordable and sustainable transport systems UN target 11.3: Inclusive and sustainable urbanisation and capacity for participatory planning and management UN target 11.5: Reduce deaths caused by disasters – e.g. fires and pollution related UN target 11.6: Reduce adverse per capita environmental impact of cities, including waste management UN target 11.7: Universal access to safe, inclusive green and public spaces UN target 11b: Adaptation to climate change, resilient to disasters UN target 11c: Support least developed countries in building sustainable and resilient buildings and utilising local materials	Mapping growth of slums / informal settlements (land dynamics) Selecting case studies of the informal settlements Identifying the slum typology Mapping population dynamics Population flows - Age category - Household typology - Growth of slumsMapping infrastructure Mapping land use dynamics Proportion of financial support to least developed countries	Recreation Shelter Transportation Urban planning Number of city data observatory Household typology instead of dwelling density
SDG 12: Responsible consumption and production UN target 12.2: Achieve sustainable management and efficient use of natural resources UN target 12.5: Reduce waste generation through prevention, reduction, recycling and re-use UN target 12b: Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products	Responsible consumer and household behaviours Resource consumption by household typology	Environment Solid waste Energy use by household typology Water use by household typology Investment in interventions for waste reduction Waste generation by waste type and household typology Energy use by building typology Number of city data observatory
SDG 13: Climate action UN target 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	Mapping disasters – e.g. fires	Number of fire disasters Number of deaths related to fire disasters Number of deaths from indoor pollution

SDG 14 Life below water		
SDG 15: Life on land UN target 15.1: Conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystem	Mapping land use changes	
SDG 16: Peace, just and strong institutions UN target 16.7: Ensure responsive, inclusive, participatory and representative decision-making at all levels	Co-designing with communities Community based research centres	Safety Fire and emergency response Governance Number of community based research centres
SDG 17: Global partnership for sustainable development Enhance capacity-building support to developing countries to increase availability of high quality, timely and reliable data	Transdisciplinary research that aims at co-designing, co-researching and co-learning Investment in data collection City data observatory	Finance

Source: Authors

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106746.

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