Journal of Cleaner Production 314 (2021) 128020

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Benchmarking urban performance against absolute measures of sustainability – A review

Kylie Goodwin[a,*], Thomas Wiedmann[a], Guangwu Chen[a,b], Soo Huey Teh[a]

[a] Sustainability Assessment Program (SAP), School of Civil and Environmental Engineering, UNSW Sydney, NSW, 2052, Australia
[b] School of Environment, Beijing Normal University, Beijing, 100875, China

ARTICLE INFO

Handling editor: Zhifu Mi

Keywords:
Absolute sustainability
Consumption-based accounting
City sustainability
Planetary boundaries

ABSTRACT

Cities are a key target in the global quest for sustainability and are increasingly acting independently to take the lead in sustainability initiatives. To truly achieve sustainability, cities need to ensure that their consumption is compatible with absolute sustainability and validate achievements from a perspective that includes transboundary impacts. The aim of this review is to assess how well these topics are incorporated into commonly used urban sustainability assessment methods, using the safe and just space (SJS) framework definition of a minimum acceptable threshold for both ecological stability and standard of living. The review identified 277 different sustainability indicator frameworks that have been applied to cities and undertook a detailed assessment of the most commonly cited of these. Consumption-based footprint studies were separately assessed to determine the extent to which they measure SJS indicators for cities. Both indicator frameworks and footprint studies had a focus on boundaries of increasing risk, including carbon, water, and land use; however few measured highly exceeded boundaries including nitrogen and phosphorus use, biodiversity, and possibly chemical pollution. Social impacts were well covered in indicator frameworks, except food intake, but largely absent from footprint studies. Cities are largely not measuring their impact on planetary tipping points or transboundary impacts, risking resolving some environmental issues while exacerbating others.

1. Introduction

1.1. City challenges and opportunities

Cities take advantage of divisions of labour and economies of scale, supporting the development of specialised services and networks. As cities grow they become hotspots of creativity and economic growth, but also increasing energy use, rates of crime, traffic congestion and disease (Batty, 2008; Bettencourt and West, 2010; Bristow and Kennedy, 2015).

It is estimated that by 2030 urban areas will house 60% of people globally, with megacities (those with over 10 million inhabitants) increasing from 33 in 2018 to 43 in 2030, mostly located in developing countries (UN, 2018). While the majority of infrastructure and urban areas are yet to be built, infrastructure and urban form lock in patterns of land use, transport choice, housing and behaviour (IPCC, 2014), with significant potential environmental impact (Bai et al., 2018).

The resource use of cities is a key determinant of world sustainability (IPCC, 2014) and understanding the interactions, tipping points, thresholds and limits of urbanisation is imperative to transition to sustainability (Seto et al., 2017). Cities are dependent on the availability of hinterlands for resources and to dissipate entropy (Bristow and Kennedy, 2015; Lenzen and Peters, 2010; Seto et al., 2017), and accordingly a critical component of city sustainability is understanding whether or not the total of a city's activities are compatible with maintaining a liveable environment.

Given that cities are essential to achieving sustainability, scientifically rigorous approaches to city sustainability measurement are needed. This paper focuses on two concepts that aim to enable clear consistent measurement of sustainability – absolute sustainability and consumption based accounting, with a focus on how they are currently embedded in key city sustainability assessment schemes, including indicator frameworks and urban metabolism approaches.

1.2. Defining sustainability

Sustainability is an evolving concept, with many attempts to define and operationalise the sustainability across different disciplines and scales, so as to optimise the trade-off between planetary resources and

* Corresponding author.
E-mail address: kylie.goodwin@unsw.edu.au (K. Goodwin).

https://doi.org/10.1016/j.jclepro.2021.128020
Received 16 December 2020; Received in revised form 31 May 2021; Accepted 17 June 2021
Available online 21 June 2021
0959-6526/

human needs (Patterson et al., 2017; Sala et al., 2015; Turcu, 2013).

Absolute environmental sustainability assessment (AESA) refers to the use of environmental sustainability indicators that are benchmarked against environmental carrying capacity (Bjørn et al., 2016; Vea et al., 2020), of which planetary boundaries (PB) are a widely used approach. These nine boundaries (see Fig. 4) are posited as the thresholds of tipping points leading to abrupt and potentially irreversible changes in planetary conditions, to an extent unfavourable to human development (Rockström et al., 2009).

Some planetary boundaries are defined as a total global limit, such as climate change and ozone depletion, while others comprise cumulative individual regional thresholds, including nitrogen and phosphorus, land cover, biodiversity, aerosols, freshwater use and chemical pollution (Dao et al., 2015; Paul Lucas and Harry Wilting, 2018).

Planetary boundary targets were originally set at a total global level, however in order to operationalise the concept at a more granular level an active body of research is considering how to allocate fair resource shares to national, regional, industry and now city levels (Li et al., 2021). Typically researchers have used an equal per capita share of the global safe operating space, although assumptions about population levels and timescales vary (Ryberg et al., 2020).

Inclusion of social indicators in sustainability analyses is essential to understand the interdependencies between societal well-being and use of biophysical resources (Haberl et al., 2019). The Safe and Just Space (SJS) concept expands the planetary boundary concept by defining an additional 12 indicators of basic human needs derived from the Sustainable Development Goals (see Fig. 5) (Raworth, 2012). Meeting these needs is posited as a “social foundation” required to achieve social as well as environmental sustainability.

Assessing sustainability on an absolute basis is essential to avoid exceeding the capacity of the earth to maintain a stable environment that remains conducive to human development (Steffen et al., 2015), and accordingly it is imperative to embed this concept at multiple scales including the city scale.

1.3. Consumption-based sustainability assessment

A critical focus of sustainability thought is determining behavioural changes required to reach desired outcomes (Schröder et al., 2019), and relies on identification of key stakeholders and processes.

Territorial and production-based accounting (PBA) approaches attribute impacts to where they are produced (Ottelin et al., 2019), while consumption-based accounting (CBA) attributes impacts to the ultimate purchaser and allocates to an entity both their own territorial emissions and upstream external supply-chain impacts of goods and services purchased, less any exports/sales.

CBA is a more complicated and resource intensive process than PBA, with a high level of assumptions required (Afionis et al., 2017; Ottelin et al., 2019), however it is especially relevant for cities, with recent studies showing a majority of city footprints are generated outside the city boundaries (Athanassiadis et al., 2018; Lenzen et al., 2020; Li et al., 2020). CBA helps avoid “leakage” of high-impact activities to extra-territorial trade and helps end-users target ‘hotspot’ consumption categories (Sudmant et al., 2018).

CBA results are often badged as “footprints”, defined as “indicators of human pressure on the environment” (Hoekstra and Wiedmann, 2014).

Hybrid approaches include varying combinations of territorial and transboundary impacts, often focused on infrastructure related emissions for carbon (such as Scope 2 carbon emissions) (Chavez and Ramaswami, 2013; Chen et al., 2019, 2020, 2020; Teh et al., 2018; Wiedmann et al., 2020a; Ramaswami et al., 2021).

A comprehensive understanding of absolute sustainability of cities requires both a territorial (production) and a consumption-based approach (Fang et al., 2015; Wiedmann et al., 2020; Wiedmann and Allen, 2021).

Comparison of CBA and PBA total impact levels enables entities to understand whether to best focus on local impacts or on transboundary impacts (Wiedmann et al., 2021; Ramaswami et al., 2021). This is particularly important for cities, because cities are more trade exposed and dependent on other regions than any other form of human settlement.

While PBA approaches have historically been the default approach taken to assess environmental impacts, CBA measurement of environmental impacts is less well understood and accordingly this review specifically focuses on the extent of CBA in city sustainability measurement.

1.4. City sustainability assessment

1.4.1. Sustainability measurement approaches

Multi-dimensional sustainability assessment of cities is predominantly undertaken using a proliferation of indicator frameworks (Cohen, 2017; D'Alpaos and Andreolli, 2020; Huovila et al., 2019; Merino-Saum et al., 2020; Verma and Raghubanshi, 2018).

An alternate but not distinct strand of assessment uses a group of techniques falling under the umbrella of urban metabolism (UM) that interrogate aspects of sustainability with goals such as assessing extended supply chain and whole-of-life impacts, and modelling complex interactions between indicators. Indicators calculated individually using these approaches may then be used as input to other UM techniques or indicator frameworks (see Fig. 1 and S2.2 Supplementary data).

1.4.2. Sustainability assessment indicator frameworks for cities

Sustainability indicator frameworks are the generally accepted approach to assessing city sustainability by policy makers, and may be seen as a de-facto definition of sustainability in the urban context (Merino-Saum et al., 2020).

A quadruple bottom line approach is often used to choose categories of indicators, comprising economic, social, environmental and governance or cultural classifications (Deng et al., 2017; Sharifi, 2020; Sharifi and Murayama, 2015). Increasingly, sustainable city concepts are being subsumed into smart city concepts and indicator sets (Huovila et al., 2019; Marvin et al., 2015; Sharifi, 2019; Yigitcanlar and Kamruzzaman, 2018), however there is not empirical evidence that an increase in city “smartness” is correlated with an increase in city sustainability performance (Yigitcanlar and Kamruzzaman, 2018).

Despite the level of effort expended developing indicator frameworks there is still a lack of consistency in definitions and indicators, and schemes are frequently based on expert opinion rather than alignment with core sustainability principles and science-based targets, which may limit their general applicability, comparability and relevance (Cohen, 2017; Feleki et al., 2018; Mischen et al., 2019; Pedro et al., 2019; Sharifi, 2020; Verma and Raghubanshi, 2018). Issues in accessing timely, reliable data, both to undertake assessments and benchmark results, undermine the useability of indicator schemes as a management tool (Huovila et al., 2019; Mischen et al., 2019; Sharifi, 2020).

Recent reviews have considered city sustainability framework indicators as mapped to SDGs (Merino-Saum et al., 2020; Zinkernagel et al., 2018), triple bottom line categories (Feleki et al., 2018; Huovila et al., 2019; Kumar et al., 2020; Massaro et al., 2020), and type of indicator, such as MONET and STEEP categorisations (Merino-Saum et al., 2020) and Input/Process/Output/Outcome/Impact and “soft” or “hard” sustainability categorisations (Huovila et al., 2019).

Others categories considered include city sectors (Huovila et al., 2019), or other self-defined themes (D'Alpaos and Andreolli, 2020; Pedro et al., 2019; Sharifi, 2020, 2019). These lenses have been applied to a wide and varied selection of indicator frameworks (see S2.1 Supplementary data).

None of these reviews, however, have looked at the use of planetary boundary indicators within frameworks, or assessment of transboundary impacts.

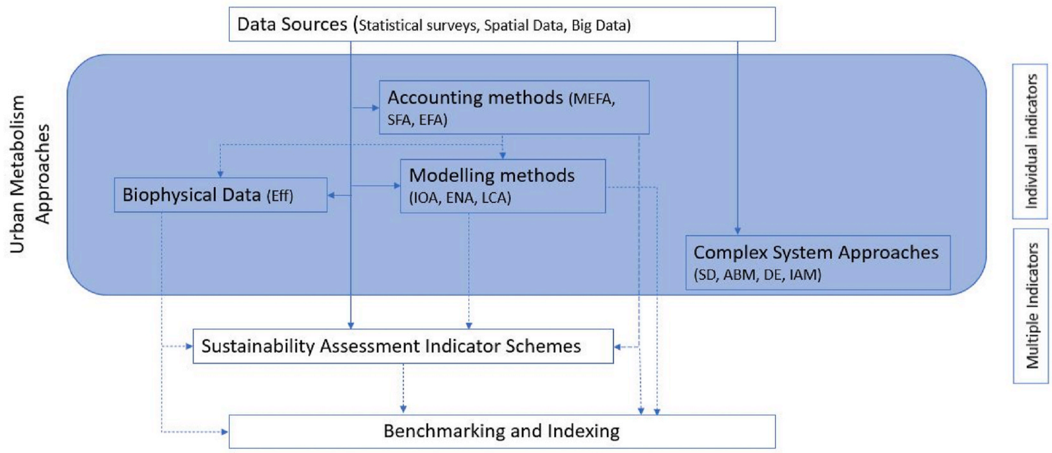

Fig. 1. Relationship between city sustainability assessment approaches. MEFA = Materials and energy flow analysis, SFA = Substance flow analysis, EFA = Ecological footprint analysis, Eff = Efficiency calculations, IOA=Input-output analysis, ENA = energy networks analysis, LCA = Life cycle assessment, SD = System dynamics, ABM = Agent-based modelling, DE = Discrete events, IAM = Integrated assessment models.

1.4.3. Urban metabolism approaches

Urban metabolism (UM) is commonly defined as "the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007), although the concept has subsequently been expanded to include subsets of processes, and processes occurring outside cities (Beloin--Saint-Pierre et al., 2017). UM approaches are widely used as a tool to model sustainability of urban areas by researchers and academics.

Techniques under this umbrella include accounting methods such as material and energy flow analysis, and modelling methods, such as life cycle assessment (LCA) (Bjorn et al., 2020), and input/output analysis, which have also been combined in various ways to form hybrid approaches (Cui, 2018; Morris et al., 2020; Song et al., 2019; Zhang et al., 2015). System based approaches used for cities (largely systems dynamics and agency modelling based) are also categorised as UM approaches (Musango et al., 2017).

Approaches vary based on time frames, type of data used, use of physical or virtual flows and whether results produced are on a production or consumption basis (See S2.2, Supplementary data).

UM approaches are increasingly used to enable the calculation of consumption-based impacts, especially multi-region input-output analysis, which is frequently used in CBA and has been identified as essential for cities to accurately assess consumption based impacts without significant truncation errors (Fry et al., 2018).

No comprehensive LCA assessments for cities have been completed, although first attempts at upscaling hybrid urban metabolism/LCA approaches have been proposed (González-García et al., 2019; Maranghi et al., 2020; Mirabella et al., 2019).

Recent reviews of urban metabolism approaches have identified methods frequently used (Beloin-Saint-Pierre et al., 2017; Shmelev and Shmeleva, 2019; Song et al., 2019) and indicators targeted (Cui, 2018; Shmelev and Shmeleva, 2019; Song et al., 2019) or focused on particular tools such as LCA (Mirabella et al., 2019), however have not analysed these against planetary boundaries explicitly, and rarely consider social outcomes (Céspedes Restrepo and Morales-Pinzón, 2018).

1.4.4. Benchmarking and indexing

Ranking approaches are used to identify relative weightings of different indicators to generate an index value, or determine key indicators, and include data envelopment analysis (DEA), multi-criteria decision analysis (MCDM), analytical hierarchical process (AHP) and VIKOR multicriteria optimization and compromise solution (Ameen et al., 2015; Suganthi, 2018). Different aggregation techniques can significantly affect rankings (Laslett and Urmee, 2020).

1.5. City-specific sustainability policy targets

Cities are increasingly acting independently of national governments to taking the lead in targeting sustainability in global networks (Bai et al., 2019), with initiatives such as ICLEI (International Council for Local Environment Initiatives, 2020), C40 cities (C40 Cities, 2020) and GCOM (Global Covenant of Mayors for Climate and Energy, 2020).

Sustainability policy mechanisms include price-based, rights-based, regulatory, legal, information and financial instruments (Sterner et al., 2019). Additionally, at a city level, several unique areas can be targeted, include infrastructure provision, spatial planning and public service provision, and these are frequently included in sustainability indicator frameworks.

City-specific infrastructure is central to many urban sustainability policy initiatives and assessments (Sterner et al., 2019), and includes the built environment, public spaces, transport, energy and waste management systems, telecommunications, water supply and treatment (Ramaswami et al., 2016). Much of this infrastructure is publicly owned or regulated and can have a significant impact on sustainability outcomes (Chen et al., 2020; Creutzig et al., 2016).

Additionally, urban planners target sustainability outcomes with indicators specific to urban areas include liveability, density and walkability (Garau and Pavan, 2018; Hake et al., 2016; Newton, 2012; Ottelin et al., 2019).

Increasing population density via built environment regulation is a key policy lever used in urban planning, such as compact city policies. Increasing density has been linked to a reduction in both local water usage under drought and regional biodiversity loss (Pautasso, 2007; Schreiber, 2016), however when viewed on a consumption basis increased density has often been shown to correlate with increased rather than reduced carbon footprints (Ottelin et al., 2019), with an increase in long-distance leisure travel (Czepkiewicz et al., 2018).

Finally, public services including cultural activities, health and education, social services, emergency services and governance can have a significant impact on achievement of social goals, and are often measured in sustainability assessment schemes, but focusing on local outcomes only (Feleki et al., 2018; Merino-Saum et al., 2020; Sharifi, 2020).

Understanding the impact of city policy targets on planetary boundaries would enable translation of absolute sustainability objectives to policy-relevant outcomes.

1.6. *Motivation and review questions*

Initial attempts by cities to measure sustainability have generally focused on relative performance (benchmarked against historic performance or other cities) and events within city boundaries. The planetary boundaries concept has quantified for the first time an overarching framework of multiple critical environmental thresholds, which enable cities to identify and prioritise key environmental goals (Wiedmann and Allen, 2021). Meanwhile, efforts to address climate change have seen a shift to widespread understanding that city consumption can drive significant impacts outside city borders, which need to be addressed at a city level (C40, 2018).

With these developments, the inclusion of absolute sustainability indicators and limits (including assessment of transboundary impacts) in city sustainability assessment is now both possible and essential to enable cities to benchmark progress to a sustainable future. However, it is not yet understood to what extent these concepts are included in the many frameworks currently in use.

This literature review aims to answer the following two questions:

1. To what extent do sustainability assessments for cities refer to absolute measures such as planetary boundaries?
2. To what extent do city sustainability assessments include transboundary impacts?

This review considers both indicator frameworks used by policy-makers and urban metabolism approaches used by researchers (see Fig. 2).

2. Method

2.1. *Identification of the most frequently cited frameworks*

Web of Science (Birkle et al., 2020) was searched to identify recent sustainability assessment review articles from 2017 to 2020 using the search terms below. These abstracts were then scanned to identify those that were specifically targeted at sustainability assessment of cities. These articles were then read and further references were identified from forward and backward citations. This resulted in a final list of 39 sustainability assessment of cities reviews from 2017 to 2020 (see S2.1 Supplementary data).

Search term	Number of Results, 2017–2020
(AB=(City OR Cities OR Urban) AND ALL=(sustain* (assessment OR appraisal))) *AND* **LANGUAGE:** (English) *AND* **DOCUMENT TYPES:** (Review)	250
AB=(“ City” OR " Cities” OR Urban) AND AB=(sustain* (assessment OR appraisal)) Refined By: **WEB OF SCIENCE CATEGORIES:** (GREEN SUSTAINABLE SCIENCE TECHNOLOGY OR ENVIRONMENTAL STUDIES OR ENGINEERING ENVIRONMENTAL OR URBAN STUDIES OR REGIONAL URBAN PLANNING OR GEOGRAPHY OR ECOLOGY OR ECONOMICS OR MULTIDISCIPLINARY SCIENCES)	1107

The 39 review papers were then read to determine which indicator schemes and frameworks were discussed or mentioned in the review articles with or without providing a formal citation. Overall, 28 review articles published between 2017 and 1 Sept 2020 met the criterion of considering different suites of indicators. These articles identified 469 references to sustainability indicator frameworks, with 277 individual frameworks mentioned up to nine times each (See Fig. 3 and S1.1 Supplementary data). Of these, 179 frameworks were mentioned only once, and a further 61 were mentioned twice.

These indicator schemes references were checked for details of year published and author/institution, and errors corrected where identified. A number of schemes did not have a year associated; however their age can be inferred from the fact they were predominantly included in review articles published in 2017.

Schemes were then grouped into developer and target-based categories based on observable clusters, as shown in Table S2.2, Supplementary data.

The top 20 cited schemes, all of which had been mentioned four or

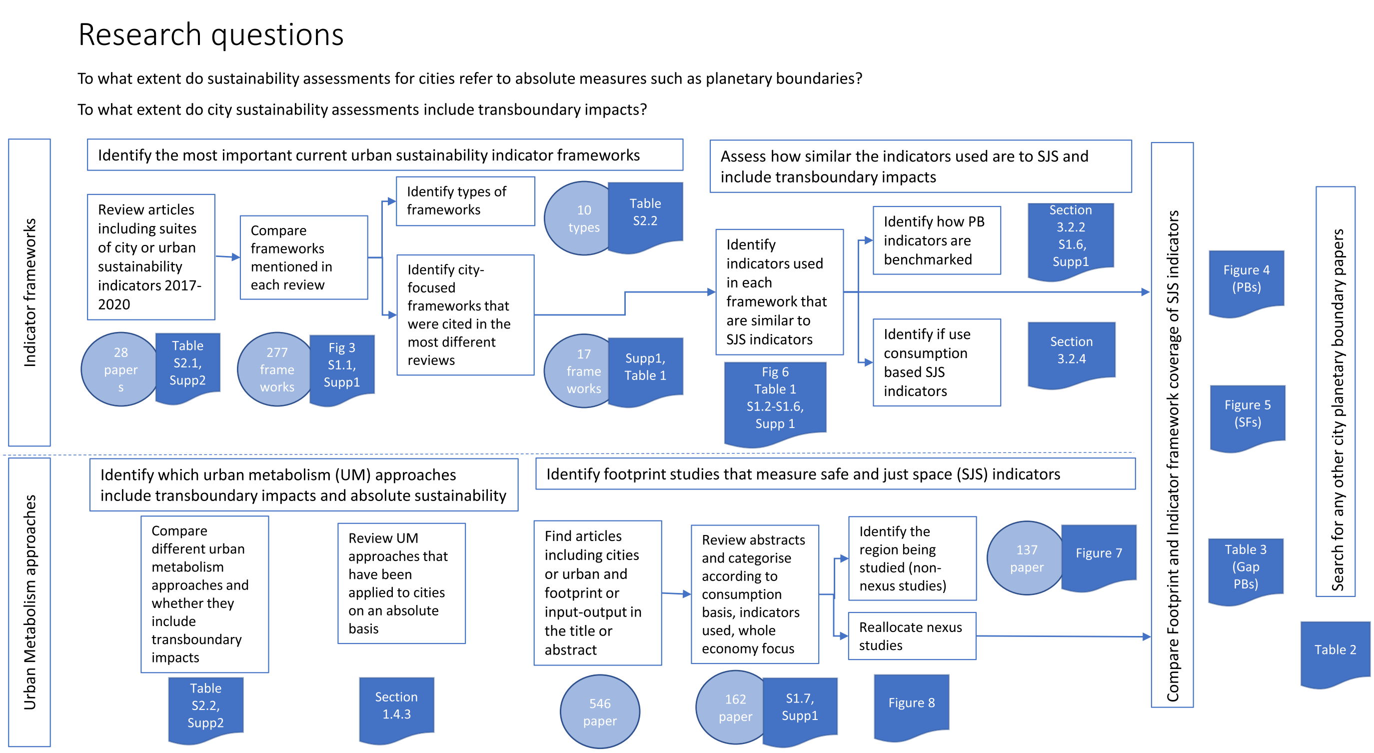

Fig. 2. Map of research approach and outputs.

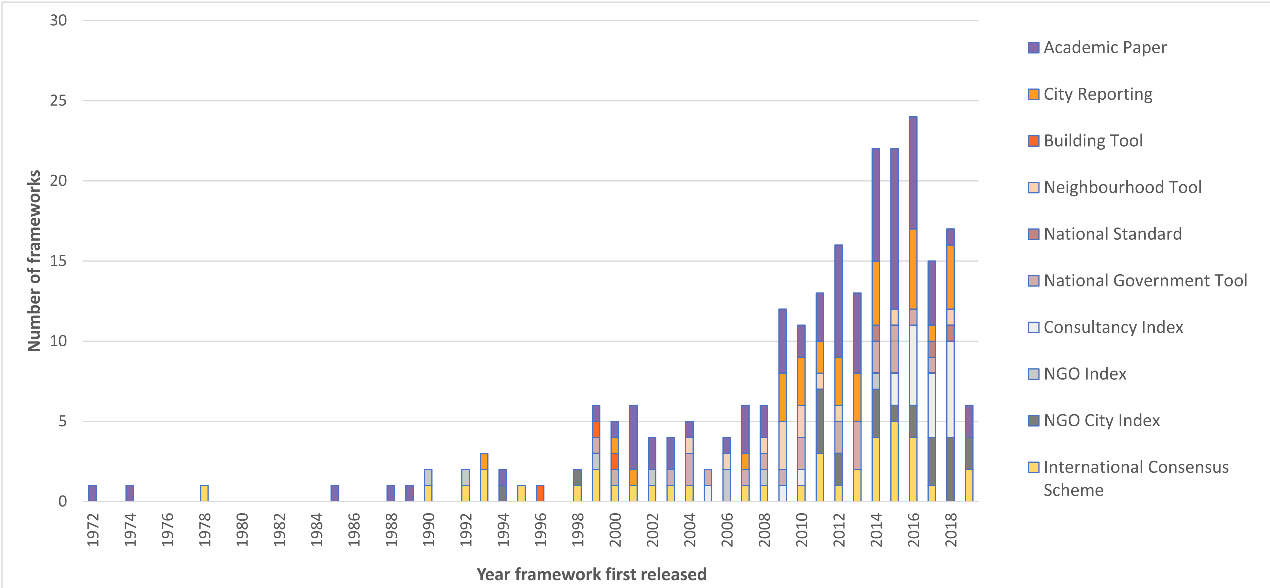

Fig. 3. City sustainability indicator frameworks cited in city sustainability review articles published from 2018 to 2020 by type and year first released.

more times, were reviewed for actual application at a city level, resulting in four being discarded from further analysis. Notably many of the most popular schemes are pre-2010, showing the slow speed of adoption of new frameworks.

Frameworks first published in 2018–2019 were also reviewed, as they are inherently less able to have been reviewed in the time frame, checking for categories that were highly cited previously (consultancy index, international consensus scheme, neighbourhood tools) and direct targeting of sustainability of cities (as opposed to liveability, smart city, resilience etc), and a further scheme (LEED v4.1 for Cities and Communities (USGBC, 2020)) was also added for further analysis, resulting in a final list of 17 indicator frameworks for detailed analysis (see Table 1).

2.2. Review of identified frameworks for absolute sustainability indicators

A detailed review of the 17 indicator schemes identified previously was undertaken to identify any indicators relating to the safe and just space (social foundations and planetary boundaries). Related indicators were interpreted generously, and indicators were either then identified as being similar or partially covering the SJS topic area (see S1.2-S1.6, Supplementary Material). Both similar and partially addressing indicators were included in the count of absolute sustainability related indicators.

Indicators were also scanned for whether they were to be measured on a consumption or production basis, and whether they were benchmarked against planetary boundaries.

2.3. Review of consumption-based urban metabolism studies

A review of consumption-based urban metabolism studies of cities was identified using a search of web of science from 2018 to 2020 (see S1.7 Supplementary data). To keep the number of studies to a reasonable level and target those most likely to be relevant to the topic several searches were run looking for "City" or "cities" or "urban" in the title, and "input output" or "input-output" or "footprint" in the title or abstract. A further search looked for those studies with all three terms in the abstract only. This returned a total of 546 papers.

The abstracts of identified papers were then read and papers were categorised based on observable clusters, whether they were consumption-based, indicators used, and whether these covered the whole economy or only subsectors (such as a particular industry, or types of households). This process resulted in identification of 162 consumption-based studies that relate to all sectors of a city, of which 25 calculated multiple different footprints, resulting in 209 total instances of footprints being identified (see S1.7 Supplementary data). With the exception of ecological footprint studies, consumption-based studies were equally or more likely to be returned using a search on the term "input output" than on the term "footprint", potentially due to the popularisation of "footprint" terminology to refer to spatial impacts, and "reducing carbon footprint" and similar terms as common aspirational phrases in environmentally targeted studies.

2.4. Review of absolute sustainability of cities studies in academic and grey literature

A further Web of science search of articles relating specifically to cities and planetary boundaries was performed, resulting in 77 results.

ALL=(City or Cities or Urban) and all=("planetary boundar*") not all = ("boundary layer")
Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI–S, CPCI-SSH, BKCI–S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = 2011–2020

These were reviewed for assessments of city sustainability, with two documents returning a combination of city, and sustainability assessment against planetary boundaries.

Science Direct was searched using Title, abstract, keywords: (" city" OR "cities" OR " urban") AND ("planetary boundaries") NOT ("planetary boundary layer") from 2011 to 2020 and returned 7 results, also with no documents returning a combination of city and sustainability assessment against planetary boundaries.

A further search of grey literature using Google identified the Thriving Cities Initiative (2020) as including city sustainability assessment against planetary boundaries.

3. Results

3.1. Overview of planetary boundary and SJS social foundation coverage

Both sustainability indicator frameworks and urban metabolism approaches frequently address the climate change planetary boundary,

Table 1
Top urban sustainability indicator frameworks by inclusion in sustainability assessment reviews 2017–2020.

Type	Assessment Scheme	Year First Released	Developed By	Cited	PBs (9)	SFs (13)	Sim %
Consultancy Index	European Green City Index	2009	Economist Intelligence Unit and Siemens (Economist Intelligence Unit, 2009)	9	3	3	67
	ARCADIS Sustainable Cities Index	2015	Arcadis/London Economic Research Institute Centre for Economics and Business Research (CEBR) (Arcadis, 2018)	6	5	8	77
International Consensus Scheme	City Prosperity Index/Global City Report	2012	UN HABITAT (UN Habitat, 2016)	9	3	12	87
	ISO 37120 Sustainable cities and communities — Indicators for city services and quality of life	2014	International Standards Organisation, Switzerland (International Standards Organisation, 2018)	9	7	13	85
	City Development Index/Global Urban Indicators Database	1993	UN HABITAT (UN Habitat, 2004)	6	1	11	92
	Sustainable Development Goals (SDGs)/SDG 11+	2015	United Nations (United Nations Statistics Division, 2016)	6	9	13	95
	Environmental Performance Index†	2002	Yale University and Columbia University (collaborating with World Economic Forum and European Commission)	5	Not Analysed		
	Human Development Index†	1990	United Nations Development Programme	4	Not Analysed		
	Indicators of Sustainable development†	1995	United Nations Commission on Sustainable Development (CSD)	4	Not Analysed		
	Global City Indicators Facility (Pre ISO 37120)	2007	Global Cities Institute (Global City Indicators Facility, 2008)	4	1	11	83
National Gov't Tool	Reference Framework for European sustainable cities	2008	RFSC (French Ministry in charge of housing and urban development et al., 2008)	5	6	11	88
Neighbourhood Tool	BREEAM Communities	2009	Building Research Establishment Ltd, UK (BRE Global Limited, 2017)	8	4	7	36
	LEED for Neighbourhood Development	2009	US Green Building Council (USGBC, 2018)	8	4	7	27
	CASBEE Urban Development	2006	Institute for Building Environment and Energy Conservation, Japan (IBEC, 2014)	6	3	7	10
	STAR Sustainability Tools for Assessing and Rating Communities Community Rating System	2008	ICLEI - Local Governments for Sustainability, US Green Building Council and Center for American Progress (S.T.A.R. Communities, 2016)	5	6	13	74
	DGNB Urban Districts	2009	German Sustainable Building Council (DGNB GmbH, 2020)	4	6	1	71
	Green Star Communities	2012	Green Building Council Australia (Green Building Council of Australia, 2012)	4	4	8	17
NGO City Index	Global Power City Index	2018	The Mori Memorial Foundation's Institute for Urban Strategies (The Mori Memorial Foundation, 2019)	4	2	6	75
	LEED for Cities and Communities*	2019	US Green Building Council (USGBC, 2020)	1	7	12	67
	Ecological Footprint/National Footprint Accounts	1992	Wackernagel and Rees/Global Footprint Network (Borucke et al., 2013)	9	3	0	89
	Environmental Sustainability Index†	1999	Yale University and Columbia University	5	Not Analysed		

PB number of planetary boundary topic areas covered in framework.
SF number of social foundation topic areas covered in framework.
Sim – % of indicators used that were rated as quite similar to SJS indicators.
†Not analysed due to only being applied to countries.
* Added in despite not being frequently cited due to recent publication.

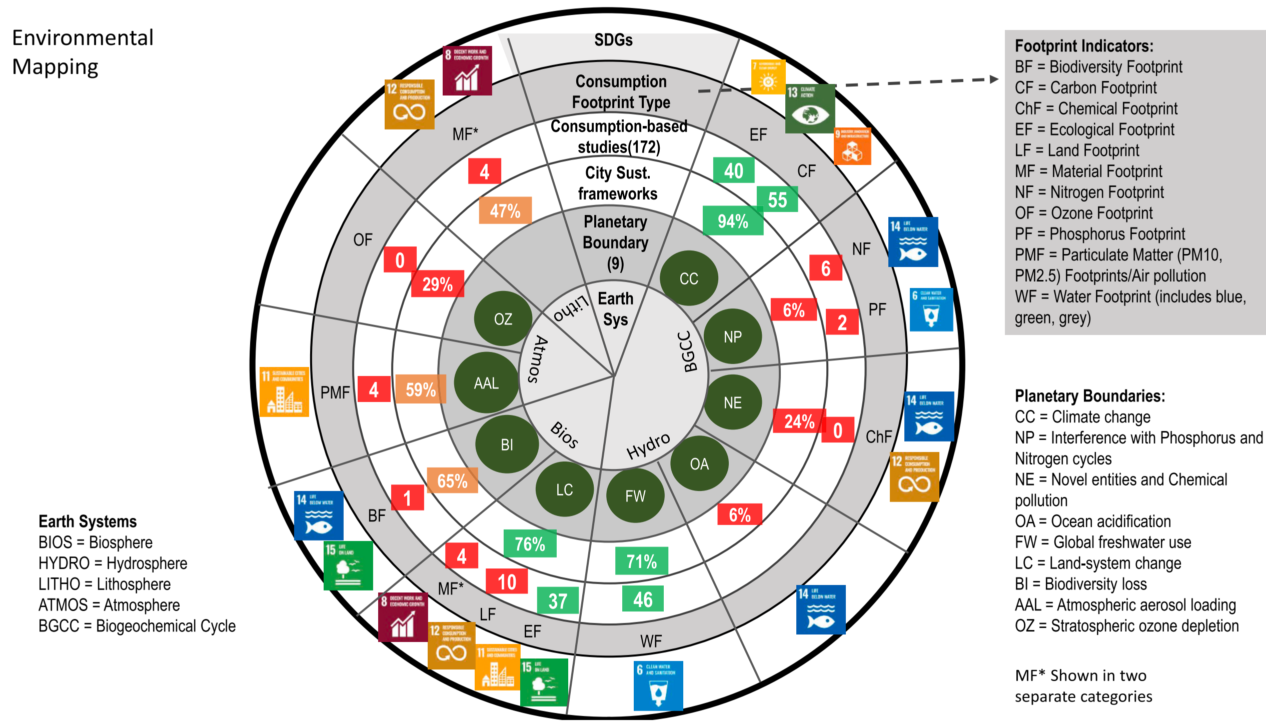

Fig. 4. Coverage of planetary boundaries in city sustainability frameworks and consumption-based studies 2018–2020. Rings of data from centre out show earth systems, planetary boundaries, % of analysed city sustainability frameworks including indicator, number of related footprint studies, footprint type, and SDGs. Green colouring indicates high coverage, yellow moderate coverage, and red low coverage.

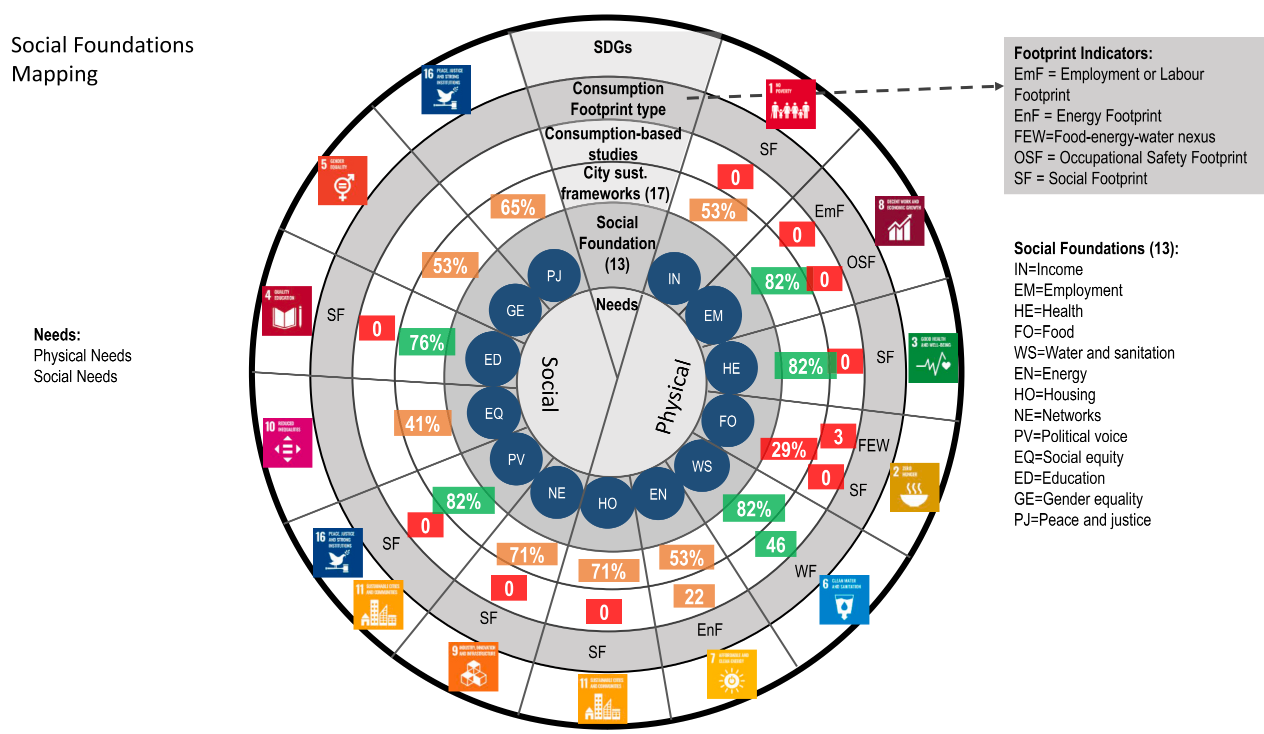

Fig. 5. Coverage of social foundations in city sustainability frameworks and consumption-based studies 2018–2020. Rings of data from centre out show need types, social foundations, % of analysed city sustainability frameworks including foundation, number of related footprint studies, footprint type, and SDGs. Green colouring indicates high coverage, yellow moderate coverage, and red low coverage.

and slightly less often land-system change and water boundaries (Fig. 4). Nitrogen and phosphorus flows, chemical pollution, ocean acidification and stratospheric ozone depletion, by contrast, are largely not considered. Aerosols, biosphere integrity and materials use indicators were relatively more prevalent in sustainability frameworks than footprint studies.

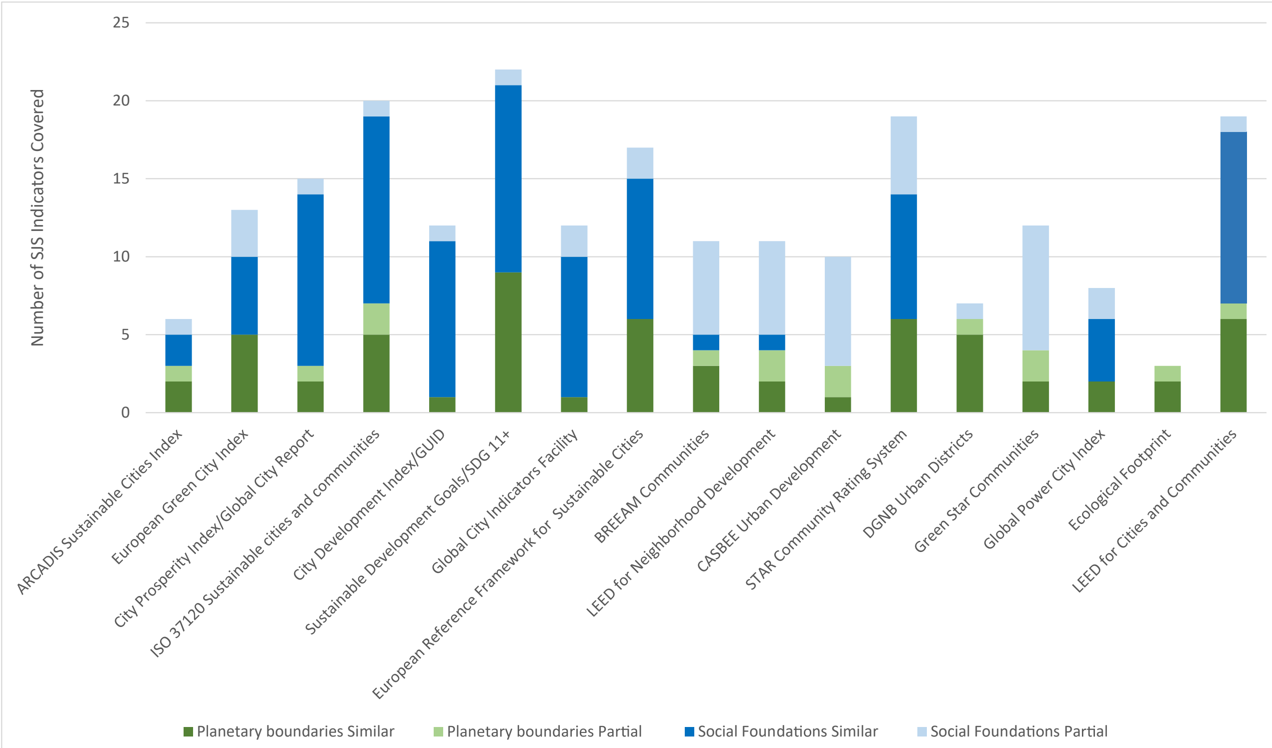

Fig. 6. Consideration of safe and just space impacts in city sustainability indicator frameworks, by type of impact and similarity to absolute sustainability indicators.

Social foundations (SF) footprints addressed energy and water use for cities but not most other foundations, however all social foundations were generally well covered in indicator frameworks (Fig. 5). The exception to this was adequacy of food intake, which was covered in several consumption-based studies but less than a third of indicator frameworks.

3.2. City assessment frameworks

3.2.1. Safe and just space coverage

Only one framework covers all PBs and SFs, being the Sustainable Development Goals, although these indicators (except those in SDG 11) are not necessarily being applied at a city scale (see Fig. 6 and Table 1). ISO 37120 had good coverage of all SJS categories except two planetary boundaries (biogeochemical flows of nitrogen and phosphorus and ocean acidification) and LEED for Cities and Communities missed the same planetary boundaries, and additionally a measurement of food sufficiency.

Of the other schemes considered a number had poor coverage of all PBs and SFs, including the European Green City Index and National Footprint Accounts.

UN Habitat indicators (City Prosperity Index and City Development Index) are heavily slanted towards social foundation indicators, while DGNB and Ecological Footprint are the only frameworks to have a better coverage of planetary boundaries than social foundation.

Indicators used were also assessed for similarity to SJS topic areas, particularly looking at indicators that addressed outcomes versus provisioning of facilities, e.g. poverty levels vs average wages, life expectancy vs number of doctors, voter participation vs project consultation, protection of land area and sprawl vs local green space, water consumption vs rainwater tank provision. Neighbourhood assessment tool indicators were typically only loosely related to SJS indicators in the same area, while international consensus frameworks and RFSC were generally well-aligned.

Overall ISO 37120 is the indicator scheme best aligned with SJS indicators for cities.

3.2.2. Benchmarking against absolute measures of sustainability

Benchmarking approaches in indicator schemes varied (see S1.6 Supplementary data), from benchmarking against other cities (e.g. European Green City Index, Sustainable Cities Index, City Prosperity Index) or targeted improvement or required proof of actions taken (e.g. SDGs, LEED for Cities and Communities, LEED for Neighbourhood Development) or various proprietary points schemes (Green Star Communities, STAR, CASBEE, BREEAM). A notable exception was the National footprint accounts, which benchmark land equivalents against biocapacity available, effectively an absolute measure of sustainability (Borucke et al., 2013). DGNB indicator set targets a climate neutral benchmark for greenhouse gas emissions only, also an absolute measure.

Initiatives to increase natural capital, such as the United Nations Decade on ecosystem restoration 2021–2030, are not typically quantified objectives in sustainability assessment schemes, although they are being targeted at a city level (Thomson and Newman, 2018).

3.2.3. Other absolute sustainability assessments of cities

A few attempts to model absolute sustainability of cities using indicator frameworks have been made, although these have not been cited in reviews yet (see Table 2), however of these, only one (Thriving Cities Initiative, 2020), considers both a consumption-based approach and a downscaled absolute boundary. That study identifies but does not quantify social indicators.

3.2.4. Consumption-based measures in indicator frameworks

Consumption-based measures in the indicator frameworks studied include greenhouse gas emissions in ISO 37120, and material footprint in the SDGs (again not specifically at a city-level). Greenhouse gas emissions are generally well understood to include a consumption (scope 2 and scope 3) component, however the indicator schemes reviewed here typically only measured direct emissions or did not specify a basis in documentation located.

Table 2
Published absolute sustainability assessments of cities.

Study	Cities	Planetary Boundary Indicators	Analysis method	Downscaling approach
(Hoornweg et al., 2016)	Toronto, Sao Paulo, Shanghai, Mumbai, Dakar	Climate change, Biodiversity loss, Freshwater use, Change in land-use, Nitrogen cycle, pollution, geophysical risk, youth opportunity, economy, energy access and intensity, mobility and connectivity, institutions, basic services, security and public safety	Indicator Sets	Global average normalized to 1
Hachaichi and Baouni (2020)	62 big cities of the Middle East and North Africa (MENA) region	CO_2, Crop, and pasture land, Harvested primary crops (HANPP), nitrogen emissions from fertilizer and manure, Phosphorus emissions from fertilizer and manure, raw material inputs, total water footprint	EE-IO	Not downscaled
(Thriving Cities Initiative, 2020)	Amsterdam	Climate change, Ocean acidification, Excessive nitrogen fertilizer use, fishing grounds, blue water footprint, ecological footprint, Waste generation, Ozone-Layer depletion, Air pollution. Local and global social goals and global social impacts are identified but not quantified	EE-IO	Divided equally among global population (CO_2 footprint decreases each year)

The Ecological Footprint is a consumption-based scheme, and this is also included as an indicator in the European refence framework for sustainable cities.

Two urban metabolism based indicator schemes identified but not frequently cited in recent reviews contain consumption-based measures, including the EEA urban metabolism scheme which includes carbon, energy, water and land footprints (Minx et al., 2011), and Kennedy megacity indicator set, which measures energy, water, material, and waste flows, but not embodied impacts (Kennedy et al., 2014).

3.3. Urban metabolism assessment

While there is limited use of consumption-based indicators identified in indicator frameworks, urban metabolism techniques, particularly input-output analysis, is being used extensively to assess consumption-based environmental impacts of cities, and to a lesser extent social impacts, with 169 different environmental footprints and 25 social footprint studies identified from 2018 to 2020, as shown in Fig. 4 and Fig. 5. The material footprint has been included in Fig. 4 despite the lack of relevant planetary boundary, as a "missing boundary" as identified by several authors (O'Neill et al., 2018; Vanham et al., 2019).

Notably half of all studies were based on cities in China, with the majority of the rest based in EU countries and North America (see Fig. 7).

While most studies focus on single indicators there were also 9 studies using multiple indicators, and 18 studies focused on nexus studies involving combinations of energy, carbon, water, food and land, as shown in Fig. 8, demonstrating the active research in this area (Arthur et al., 2019).

Numbers show quantity of studies for each nexus, e.g. there were seven identified energy-water nexus studies. Colouring and shading has been added to improve legibility.

Other areas of consumption-based study related to cities that have not been included in totals reported include assessment of particular industries and types of infrastructure, such as the construction sector, green spaces, energy, transport, waste and stormwater. Studies of different household types explore the relationship between household characteristics and environmental outcomes, such as comparing urban and rural consumption to understand impacts of increasing urbanisation. Spatial footprinting aims to quantify the land-use impact of the built environment. A number of non-consumption footprints focused on the user of remote sensing, IoT and mobile phone data to measure urban form and environmental and social data.

Input output analysis has been used widely to calculate city footprints including carbon footprints (Chen et al., 2019; Moran et al., 2018), ecological footprints (Lu and Chen, 2017) and water footprints (Garcia et al., 2020; Heck et al., 2018; Hoff et al., 2014).

4. ɒiscussion

4.1. Assessment ofabsolute sustainability in city indicator frameworks

Understanding the link between environmental impacts and city consumption is essential to meet the long-term material, social and environmental needs of city dwellers, without sending other species to extinction. This review shows that absolute sustainability assessments are still largely not incorporated into the sustainability frameworks used to benchmark city efforts. Indicators used are rarely measured from a consumption-based perspective, despite input-output based techniques being frequently used to undertake full supply-chain assessment of cities by the research community, and thus provide only a partial view of the resources required to provision cities. Similarly, while popular city sustainability assessment frameworks include assessment of many planetary boundary-related issues in some form there is a limited ability to understand the extent to which individual cities are contributing to overshoot because they are not benchmarked against planetary boundaries.

4.2. Consumption-based assessment

Thi paper found many city consumption-based footprints available for carbon, water and ecological footprints, reflecting previous studies (Matuštík and Kočí, 2021; Vanham et al., 2019; Wiedmann and Allen, 2021). Of particular use for decision makers may be an analysis of the carbon footprint of 13,000 cities (Moran et al., 2018), and water footprints from the city-sustainability.com website although city boundaries defined may vary from administrative boundaries.

Data-based decision making is intended to improve policymaking; however it needs to be recognised that data collection itself is a political process, which can artificially limit transformation possibilities and delegitimise unmeasured concerns (Hughes et al., 2020). In the case of economic data used in CBA and PBA analyses, non-market transactions and benefits are often excluded, and research to understand the impact of this on results reported would give additional confidence in conclusions drawn (Medina and Schneider, 2018).

Changes in consumption patterns, particularly relating to diet, have been identified as essential to achieve broad sustainability objectives (Sachs et al., 2019). On a micro-scale, however, individual consumers have a limited ability to affect production decisions, although group efforts can be more effective (García-de-Frutos et al., 2018).

Consumption reduction in any area is likely to lead to a rebound effect in terms of alternative spending, and demand-inducing price decreases, which will reduce the environmental benefits of the original consumption reduction (Ottelin et al., 2020; Sorrell et al., 2020; Wiedmann et al., 2020b), and identifying beneficial consumption choices may be useful in minimising this outcome.

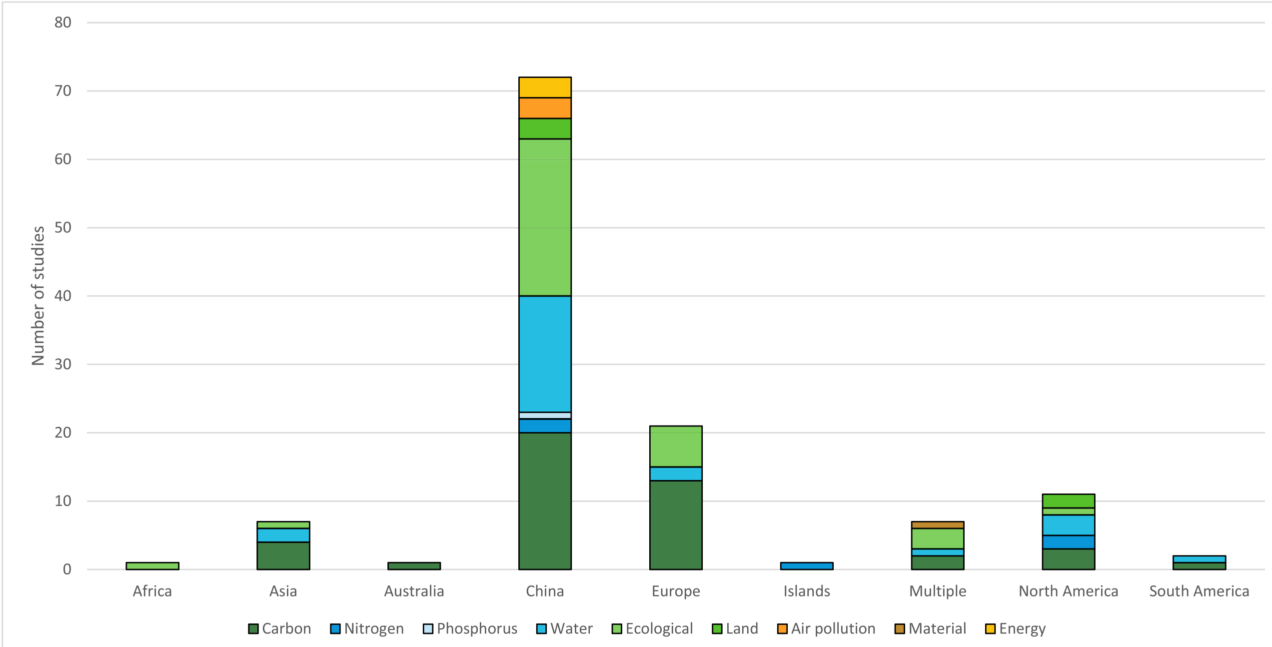

Fig. 7. Urban metabolism footprint studies by country and type. Excludes nexus and multiple indicator studies (but see Fig. 8).

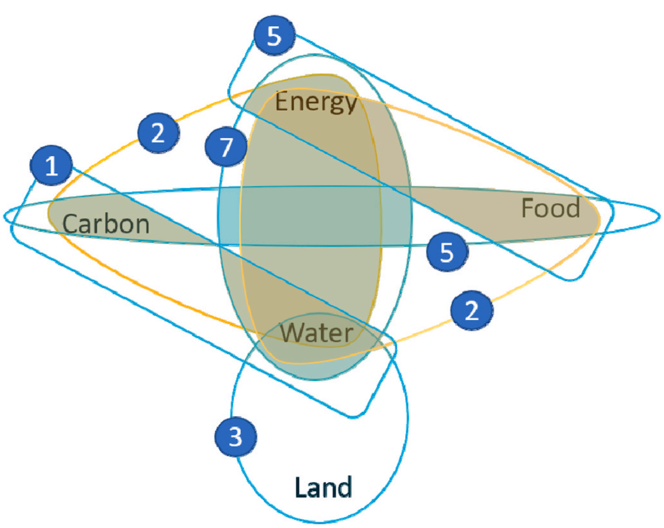

Fig. 8. Consumption based nexus studies 2018–2020.

4.3. Planetary boundary indicators in city sustainability

Of all the planetary boundaries, greenhouse gas emissions were the best incorporated into indicator frameworks (94% of frameworks), reflecting a broad understanding and public concern over this issue. Land-use change was also well-represented, reflecting concerns about density and urban sprawl, and from a footprint perspective the popularity of the Ecological Footprint measure (76% of frameworks).

Water is also frequently included (71% of frameworks) despite being one of the less-exceeded boundaries, presumably because of the immediate effect of water deficiency on human well-being. While the water usage planetary boundary currently focuses on freshwater use, five alternate sub-boundaries have recently been proposed, including soil moisture, atmospheric moisture, groundwater, frozen water and surface water (Gleeson et al., 2020b). Footprint analysis, meanwhile, has historically focused on grey (waste) water, blue (ground) water and green (rain) water footprints (Mekonnen and Hoekstra, 2011). City frameworks analysed here generally only considered freshwater and wastewater treatment availability, or total volume of water use, while footprints were a mixture of grey, blue and green water footprints.

Biodiversity loss, nitrogen and phosphorus loading and land conversion have been identified as the most overshot boundaries, and accordingly should form an area of particular focus (Steffen et al., 2015). Additionally the novel entities/chemical pollution boundary/(ies) is both unelucidated and likely to have been exceeded, and is likely to become more prominent once better defined (Diamond et al., 2015a). Apart from land use change, there was very limited assessment of these boundaries, in the city literature reviewed (see S1.6 Supplementary data).

Ocean acidification has largely not been incorporated in assessments, however is also often characterised as directly driven by the climate change boundary, and accordingly redundant (O'Neill et al., 2018).

Both aerosol loading and ozone production have largely been incorporated in indicator frameworks as reference to local concentrations only. Given that all forms of carbon combustion produce significant aerosols (Steffen et al., 2015) it is likely that addressing climate change will simultaneously address the aerosol boundary. Similarly ozone depletion has sometimes been excluded from analysis on the basis that the Montreal Protocol response is already effectively addressing this issue (O'Neill et al., 2018), so targeting both these boundaries on a consumption basis at a city scale may not be worth significant data collection effort.

A materials boundary has been suggested but not included in the planetary boundary framework. This issue has been covered in approximately half of the frameworks assessed and some consumption-based studies.

Urgent research is required for planetary boundaries that are both high-priority and not currently included in city assessments. High-priority boundaries are defined as those that are highly transgressed or undefined, independent of other boundaries (e.g. several boundaries are largely driven by burning fossil fuels and therefore are dependent on climate change mitigation), and not effectively managed (see Table 3).

4.4. Assessment of social outcomes of cities

The social foundation in the safe and just space focuses on basic

Table 3
Coverage gap for planetary boundaries in city sustainability assessment.

Planetary Boundary	Boundary Transgression (Steffen et al., 2015)	Redundancy Dependence on other boundaries/effectively managed (O'Neill et al., 2018)	Priority Level average of boundary transgression and redundancy	Literature Inclusion (from Fig. 4)	Coverage Gap (priority level less literature inclusion)
Climate Change[P]	Medium	Low	Medium	High	Low
Nitrogen/Phosphorus[P]	High	Low	High	Low	High
Chemical/Novel Entities[P]	Undefined	Low	High	Low	High
Ocean Acidification[P]	Low	High (Climate change)	Low	Low	Low
Freshwater Use[R]	Low	Low	Medium	High	Low
Land-use change[R]	Medium	Medium (Climate change)	Medium	High	Low
Biosphere Integrity	High	Low	High	Low	High
Atmospheric Aerosols[P]	Undefined	High (Climate change)	Medium	Medium	Low
Ozone Layer	Low	High (Montreal Framework)	Low	Low	Low

human needs that fit within the sufficiency perspective of the affluence vs sufficiency vs poverty paradigm., where poverty refers to an inability to meet basic needs, and affluence refers to a level of consumption that is both unessential and in excess of natural resource availability, referred to as 'overconsumption'. (Håkansson, 2014; Millward-Hopkins et al., 2020; Raworth, 2017; Wiedmann et al., 2020). Several of the indicator frameworks assessed, by contrast, were more focused on assessing the most appealing cities and urban areas to live in, especially the Global Power City Index and Arcadis Sustainable Cities Index.

Overall, all frameworks had a reasonable level of coverage of social goals except DGNB, Ecological Footprint, and the European green city index. The indicators used in neighbourhood tools were generally focused on provision of community facilities, project consultation and local employment, rather than outcomes such as life expectancy and unemployment rate.

The most common SJS indicators across all non-neighbourhood schemes were homicides per 100,000 population, access to electricity, improved shelter and access to internet, while many other social foundations had an array of measurement approaches.

Unlike the concept of staying within planetary boundaries, it is less clear that meeting social foundations for an individual city requires a consumption based approach, particularly if the SJS is conceived as a system with environmental impacts as inputs and social goods as outputs. Additionally, there is often not a clear line of causation from the general production of economic goods and services to social impacts, which may be more dependent on local political contexts than economic transactions, despite increasing trends towards social procurement policies. This is reflected in the difference between the large number of social framework indicators versus the small number of footprint analyses identified here, with the exception of water footprint which is an indirect measure of total rather than individual water access.

Social footprints for value added, employment (including indecent employment), gender equality, mother and child health, governance, corruption and access to clean water have been studied at a national level (García-Alaminos et al., 2020; Wiedmann and Lenzen, 2018; Xiao et al, 2017, 2018) to "unravel trade-implicated inequality and questions of (corporate) social responsibility" (Wiedmann and Lenzen, 2018), and have the capacity for identifying the areas in which cities are likely to be impacted by a global achievement of basic needs.

Alternative methods of social assessment include well-being assessment (Costanza et al., 2014; Kubiszewski et al., 2018), and human needs assessment (Vita et al., 2019) using frameworks such as Max-Neef or Maslow needs hierarchy (Maslow, 1943; Max-neef et al., 1992).

5. Further research needs

There is a clear need for cities to achieve absolute sustainability of cities (on both a territorial and consumption basis), however at this stage an absolute sustainability perspective has not been applied in most of the commonly used city sustainability assessment frameworks.

To assist cities in this process, further research is needed.

Firstly, planetary boundaries need to be fully understood and expounded on at a global level (Downing et al., 2019). Locally relevant cut-offs for planetary boundaries (such as freshwater use) are not well-understood and incorporated, and significant work is required to define these local boundaries globally. Chemical pollution and novel entities often negatively impact both environmental and human health and need urgent attention to establish a planetary boundary(ies) (Diamond et al., 2015; Naidu et al., 2021; Persson et al., 2019; Sala and Goralczyk, 2013). Similarly, the water boundary is currently being further refined (Gleeson et al., 2020a).

Understanding significant corollaries between both indicators and outcomes (social foundation and planetary boundaries) is needed to confirm that indicators recommended are both necessary and sufficient. For example, the biosphere boundary is highly dependent on other boundaries and has significant overlap with physical human needs (sometimes competing directly for resources), and social foundation indicators could be assessed against well-being outcomes.

Secondly, widespread city data collection and assessment of all planetary boundaries needs to be undertaken, on a consumption basis. As identified, nitrogen and phosphorus have limited research despite being the most overshot boundary, and are important in understanding the unintended consequences, and similarly biodiversity. However, all boundaries except possibly climate change are largely not considered from a consumption perspective.

Downscaled benchmarks are required as part of this process, and it is worth reconsidering the "equal per person per capita" approach that is currently commonly used, to ensure that the selection of timeframes and initial conditions do not result in unfair outcomes given that flows are being used as an approximation for natural capital stock levels. Benchmarks chosen need to appropriately consider future population growth and be congruent with reducing boundary overshoot. Consideration could be given to incorporating research on household variations by reporting indicators as the % population living within boundaries rather than average impact per capita across a population.

Geographically, existing frameworks and footprints largely focus on European, American and Chinese cities. Studies that include cities worldwide would expand knowledge, particularly looking at rapidly expanding megacities in Asia and Africa.

Thirdly, to enable cities to implement policy and track movement towards SJS on a timely basis, it would be useful to understand relationships between SJS indicators and other more immediate tools of city policy (Creutzig et al., 2019). Similarly, sustainability assessment indicators need to be functional on a cross-disciplinary basis, and operationally useful to practitioners implementing programs (Dijst et al., 2018).

Linking absolute sustainability outcomes to city design options (spatial and infrastructure) would help drive development that leapfrogs unsustainable choices. Identification of both ecologically and socially positive or negative initiatives would provide direction under conditions of future uncertainty (Saltelli et al., 2020).

Finally, detailed research on areas of known sustainability challenges would help focus effort where the greatest positive outcome is possible and untangle difficult choices. Examples of this are informal settlements, food nexus studies, and trade-offs between reforestation and alternate land and water uses.

Flipping the current focus on how those consuming more than their fair share can reduce consumption to focusing on how those not over-consuming can better meet their needs may provide further insights into socially acceptable low-consumption choices.

6. conclusion

Sustainability increasingly forms an aspiration for global citizens, with an objective of lasting prosperity for all. Global cities are to be commended for increasingly committing to net zero carbon emissions. However, the current failure to assess their impact on all planetary boundaries runs the risk of solving one environmental issue while exacerbating others.

High-risk planetary boundary pressures that are particularly poorly understood at a city level include nitrogen and phosphorus use, biodiversity, and chemical pollution; while adequate nutrition is a frequently overlooked basic social foundation despite the long-term consequences of malnutrition, and its persistence in pockets of even wealthy cities.

Measuring the transboundary impacts of cities is critical in ensuring cities have a sustainable level of resource use. While there is currently a large body of research work assessing these impacts in the field of urban metabolism, particularly for greenhouse gases, water and land use, the indicator frameworks commonly used by cities typically only measure impacts generated within city boundaries. This oversight may create perverse incentives to “offshore” impacts to external locations, generate a false sense of security, and delay effective action that could be taken.

It is recommended that as a priority all cities undergo a regular review of the compatibility of their resource use, generated both within and outside their boundaries, with planetary boundaries, and, the extent to which they are meeting basic human needs, using culturally agnostic and outcome focused measures.

This represents a base threshold level of sustainability distinct from the manifold social, environmental, and economic goals often targeted in aspirational sustainability schemes. From this basic level of sustainability information cities are then able to formulate intermediate goals and targets relevant to their circumstances, and track performance over time and between cities. Researchers need to support this with data and methodology, including an understanding of linkages between policy target areas and social and environmental outcomes.

Breaching any planetary boundary will ultimately lead to loss of productive environmental capacity with necessary impact on the ability to meet human and other species needs.

Navigating a path to an acceptable standard of living that is within the earths carrying capacity without invoking ecological population controls such as starvation, disease and violence is a substantial but worthwhile challenge. While still theoretically possible at this stage, at a minimum it requires excellent information, substantial innovation, and widespread social support for a rapid transformation to an environmentally-bounded level of total consumption.

Cities and citizens have demonstrated their ability and willingness to address environmental issues, the challenge now for the research community is to light the way with best-practice assessment methods, approaches and data at a city level.

CRediT author statement

Kylie Goodwin: Conceptualization, Methodology, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualisation. **Thomas Wiedmann**: Conceptualization, Resources, Writing – Review & Editing, Visualisation, Supervision, Funding acquisition. **Guangwu Chen**: Writing – Review & Editing. **Soo Huey Teh**: Writing – Review & Editing, Supervision.

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.

Acknowledgements

This work was financially supported by the Australian Research Council (project number DP190102277) and the Research Council of Norway (project number 287690). Guangwu Chen acknowledges the support of the China Postdoctoral Science Foundation (Grant NO. 2020M680440). Kylie Goodwin acknowledges the support of an Australian Government Research Training Program Scholarship.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128020.

References

Afionis, S., Sakai, M., Scott, K., Barrett, J., Gouldson, A., 2017. Consumption-based carbon accounting: does it have a future? WIREs Clim Chang 8, 438. https://doi.org/10.1002/wcc.438.
Ameen, R.F.M., Mourshed, M., Li, H., 2015. A critical review of environmental assessment tools for sustainable urban design. Environ. Impact Assess. Rev. 55, 110–125. https://doi.org/10.1016/j.eiar.2015.07.006.
Arcadis, 2018. Citizen centric cities. The sustainable cities index 2018. Sustain. Cities Index 32.
Arthur, M., Liu, G., Hao, Y., Zhang, L., Liang, S., Asamoah, E.F., Lombardi, G.V., 2019. Urban food-energy-water nexus indicators: a review. Resour. Conserv. Recycl. 151, 104481 https://doi.org/10.1016/j.resconrec.2019.104481.
Athanassiadis, A., Christis, M., Bouillard, P., Vercalsteren, A., Crawford, R.H., Khan, A.Z., 2018. Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities. J. Clean. Prod. 173, 112–123. https://doi.org/10.1016/j.jclepro.2016.10.068.
Bai, X., Dawson, R.J., Ürge-Vorsatz, D., Delgado, G.C., Salisu Barau, A., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D.C., Schultz, S., 2018. Six research priorities for cities and climate change. Nature 555, 23–25. https://doi.org/10.1038/d41586-018-02409-z, 7694.
Bai, X., Colbert, M.L., McPhearson, T., Roberts, D., Siri, J., Walsh, B., Webb, B., 2019. Networking urban science, policy and practice for sustainability. Curr. Opin. Environ. Sustain. 39, 114–122. https://doi.org/10.1016/j.cosust.2019.08.002.
Batty, M., 2008. The size, scale, and shape of cities. Science 319 (80), 769–771. https://doi.org/10.1126/science.1151419.
Beloin-Saint-Pierre, D., Rugani, B., Lasvaux, S., Mailhac, A., Popovici, E., Sibiude, G., Benetto, E., Schiopu, N., 2017. A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. J. Clean. Prod. 162, S223–S240. https://doi.org/10.1016/j.jclepro.2016.09.014.
Bettencourt, L., West, G., 2010. A unified theory of urban living. Nature 467, 912–913. https://doi.org/10.1038/467912a, 7318.
Birkle, C., Pendlebury, D.A., Schnell, J., Adams, J., 2020. Web of Science as a data source for research on scientific and scholarly activity. Quant. Sci. Stud 1, 363–376. https://doi.org/10.1162/qss_a_00018.
Bjørn, A., Margni, M., Roy, P.O., Bulle, C., Hauschild, M.Z., 2016. A proposal to measure absolute environmental sustainability in life cycle assessment. Ecol. Indicat. 63, 1–13. https://doi.org/10.1016/j.ecolind.2015.11.046.
Bjorn, A., Chandrakumar, C., Boulay, A.M., Doka, G., Fang, K., Gondran, N., Hauschild, M.Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., Ryberg, M., 2020. Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. Environ. Res. Lett. 15 (8) https://doi.org/10.1088/1748-9326/ab89d7.
Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M., Galli, A., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts'

underlying methodology and framework. Ecol. Indicat. 24, 518–533. https://doi.org/10.1016/j.ecolind.2012.08.005.
Bre Global Limited, 2017. BREEAM Communities Technical Manual SD202-1.2:2012.
Bristow, D., Kennedy, C., 2015. Why do cities grow? Insights from nonequilibrium thermodynamics at the urban and global scales. J. Ind. Ecol. 19, 211–221. https://doi.org/10.1111/jiec.12239.
C40, 2018. Consumption-based GHG Emissions of C40 Cities. C40 Cities Climate Leadership Group.
C40 Cities, 2020. C40 cities [WWW Document]. URL. https://www.c40.org/. accessed 11.18.2020.
Céspedes Restrepo, J.D., Morales-Pinzón, T., 2018. Urban metabolism and sustainability: precedents, genesis and research perspectives. Resour. Conserv. Recycl. 131, 216–224. https://doi.org/10.1016/j.resconrec.2017.12.023.
Chavez, A., Ramaswami, A., 2013. Articulating a trans-boundary infrastructure supply chain greenhouse gas emission footprint for cities: mathematical relationships and policy relevance. Energy Pol. 54, 376–384. https://doi.org/10.1016/j.enpol.2012.10.037.
Chen, G., Shan, Y., Hu, Y., Tong, K., Wiedmann, T., Ramaswami, A., Guan, D., Shi, L., Wang, Y., 2019. Review on city-level carbon accounting. Environ. Sci. Technol. 53 https://doi.org/10.1021/acs.est.8b07071.
Chen, S., Long, H., Chen, B., Feng, K., Hubacek, K., 2020. Urban carbon footprints across scale: important considerations for choosing system boundaries. Appl. Energy 259. https://doi.org/10.1016/j.apenergy.2019.114201.
Cohen, M., 2017. A systematic review of urban sustainability assessment literature. Sustainability 9 (11), 2048. https://doi.org/10.3390/su9112048.
Costanza, R., Alperovitz, G., Daly, H., Farley, J., Franco, C., Jackson, T., Kubiszewski, I., Schor, J., Victor, P., 2014. Building a sustainable and desirable economy-in-society-in-nature. In: State of the World 2013: Is Sustainability Still Possible? Island Press, Washington, pp. 126–142. https://doi.org/10.5822/978-1-61091-458-1_11.
Creutzig, F., Agoston, P., Minx, J.C., Canadell, J.G., Andrew, R.M., Quéré, C. Le, Peters, G.P., Sharifi, A., Yamagata, Y., Dhakal, S., 2016. Urban infrastructure choices structure climate solutions. Nat. Clim. Change 6 (12), 1054–1056. https://doi.org/10.1038/nclimate3169.
Creutzig, F., Lohrey, S., Bai, X., Baklanov, A., Dawson, R., Dhakal, S., Lamb, W.F., McPhearson, T., Minx, J., Munoz, E., Walsh, B., 2019. Upscaling urban data science for global climate solutions. Glob. Sustain. 2 https://doi.org/10.1017/sus.2018.16.
Cui, X., 2018. How can cities support sustainability: a bibliometric analysis of urban metabolism. Ecol. Indicat. 93, 704–717. https://doi.org/10.1016/j.ecolind.2018.05.056.
Czepkiewicz, M., Heinonen, J., Ottelin, J., 2018. Why do urbanites travel more than do others? A review of associations between urban form and long-distance leisure travel. Environ. Res. Lett. 13 (7) https://doi.org/10.1088/1748-9326/aac9d2.
Dao, H., Friot, D., Peduzzi, P., Chatenoux, B., De Bono, A., Schwarzer, S., 2015. Environmental Limits and Swiss Footprints Based on Planetary Boundaries. UNEP/GRID-Geneva & University of Geneva, Geneva, Switzerland.
Deng, D., Liu, S., Wallis, L., Duncan, E., McManus, P., 2017. Urban Sustainability Indicators: how do Australian city decision makers perceive and use global reporting standards? Aust. Geogr. 48, 401–416. https://doi.org/10.1080/00049182.2016.1277074.
DGNB GmbH, 2020. Certification requirements for urban districts | DGNB System [WWW Document]. URL. https://www.dgnb-system.de/en/districts/certification-requirements/index.php. (Accessed 13 October 2020).
Diamond, M.L., de Wit, C.A., Molander, S., Scheringer, M., Backhaus, T., Lohmann, R., Arvidsson, R., Bergman, Å., Hauschild, M., Holoubek, I., Persson, L., Suzuki, N., Vighi, M., Zetzsch, C., 2015. Exploring the planetary boundary for chemical pollution. Environ. Int. https://doi.org/10.1016/j.envint.2015.02.001.
Dijst, M., Worrell, E., Böcker, L., Brunner, P., Davoudi, S., Geertman, S., Harmsen, R., Helbich, M., Holtslag, A.A.M., Kwan, M.P., Lenz, B., Lyons, G., Mokhtarian, P.L., Newman, P., Perrels, A., Ribeiro, A.P., Rosales Carreón, J., Thomson, G., Urge-Vorsatz, D., Zeyringer, M., 2018. Exploring urban metabolism—towards an interdisciplinary perspective. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.09.014.
Downing, A.S., Bhowmik, A., Collste, D., Cornell, S.E., Donges, J., Fetzer, I., Häyhä, T., Hinton, J., Lade, S., Mooij, W.M., 2019. Matching scope, purpose and uses of planetary boundaries science. Environ. Res. Lett. 14 https://doi.org/10.1088/1748-9326/ab22c9.
D'Alpaos, C., Andreolli, F., 2020. Urban quality in the city of the future: a bibliometric multicriteria assessment model. Ecol. Indicat. 117, 106575. https://doi.org/10.1016/j.ecolind.2020.106575.
Economist Intelligence Unit, 2009. European Green City Index. Siemens AG. Siemens AG, Munich (Munich).
Fang, K., Heijungs, R., De Snoo, G.R., 2015. Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework. Ecol. Econ. 114, 218–226. https://doi.org/10.1016/j.ecolecon.2015.04.008.
Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2018. Characterisation of sustainability in urban areas: an analysis of assessment tools with emphasis on European cities. Sustain. Cities Soc. 43, 563–577. https://doi.org/10.1016/j.scs.2018.08.025.
French Ministry in charge of housing and urban development, The Council of European Municipalities and Regions, Cerema, 2008. Reference Framework for Sustainable Cities 5 Dimensions and 30 Objectives for a European Vision of Tomorrow's Cities.
Fry, J., Lenzen, M., Jin, Y., Wakiyama, T., Baynes, T., Wiedmann, T., Malik, A., Chen, G., Wang, Y., Geschke, A., Schandl, H., 2018. Assessing carbon footprints of cities under limited information. J. Clean. Prod. 176, 1254–1270. https://doi.org/10.1016/j.jclepro.2017.11.073.
Garau, C., Pavan, V.M., 2018. Evaluating urban quality: indicators and assessment tools for smart sustainable cities. Sustain. Times 10. https://doi.org/10.3390/su10030575.
Garcia, S., Rushforth, R., Ruddell, B.L., Mejia, A., 2020. Full domestic supply chains of blue virtual water flows estimated for major U.S. Cities. Water Resour. Res. 56 https://doi.org/10.1029/2019WR026190.
García-Alaminos, Á., Ortiz, M., Arce, G., Zafrilla, J., 2020. Reassembling social defragmented responsibilities: the indecent labour footprint of US multinationals overseas. Econ. Syst. Res. https://doi.org/10.1080/09535314.2020.1827224.
García-de-Frutos, N., Ortega-Egea, J.M., Martínez-del-Río, J., 2018. Anti-consumption for environmental sustainability: conceptualization, review, and multilevel research directions. J. Bus. Ethics 148, 411–435. https://doi.org/10.1007/s10551-016-3023-z.
Gleeson, T., Wang-Erlandsson, L., Zipper, S.C., Porkka, M., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S.E., Piemontese, L., Gordon, L.J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K.A., Flö, M., Bierkens, M.F.P., Lehner, B., Keys, P., Kummu, M., Wagener, T., Dadson, S., Troy, T.J., Steffen, W., Falkenmark, M., Famiglietti, J.S., 2020a. One earth perspective the water planetary boundary: interrogation and revision. One Earth 2, 223–234. https://doi.org/10.1016/j.oneear.2020.02.009.
Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S.C., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S.E., Piemontese, L., Gordon, L.J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K.A., Flörke, M., Bierkens, M.F.P., Lehner, B., Keys, P., Kummu, M., Wagener, T., Dadson, S., Troy, T.J., Steffen, W., Falkenmark, M., Famiglietti, J.S., Wang-Erlandsson, L., Porkka, M., Zipper, S.C., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S.E., Piemontese, L., Gordon, L.J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K.A., Flörke, M., Bierkens, M.F.P., Lehner, B., Keys, P., Kummu, M., Wagener, T., Dadson, S., Troy, T.J., Steffen, W., Falkenmark, M., Famiglietti, J.S., Gleeson, A.L., 2020b. Illuminating water cycle modifications and Earth system resilience in the Anthropocene. Water Resour. Res. 56 https://doi.org/10.1029/2019WR024957.
Global City Indicators Facility, 2008. Preliminary Final Report Global City Indicators Program Report - Part of a Program to Assist Cities in Developing an Integrated Approach for Measuring City Performance. GCIF, University of Toronto.
Global Covenant of Mayors for Climate and Energy, 2020. Global covenant of Mayors for climate and energy [WWW Document]. https://www.globalcovenantofmayors.org/ (accessed 11.18.2020).
González-García, S., Dias, A.C., González-García, S., Dias, A.C., 2019. Integrating lifecycle assessment and urban metabolism at city level: comparison between Spanish cities. J. Ind. Ecol. 23, 1062–1076. https://doi.org/10.1111/jiec.12844.
Green Building Council of Australia, 2012. Green Star Communities Guide for Local Government.
Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173–184. https://doi.org/10.1038/s41893-019-0225-2.
Hachaichi, M., Baouni, T., 2020. Downscaling the planetary boundaries (Pbs) framework to city scale-level: de-risking MENA region's environment future. Environ. Sustain. Indic. 5, 100023. https://doi.org/10.1016/j.indic.2020.100023.
Håkansson, A., 2014. What is overconsumption? - a step towards a common understanding. Int. J. Consum. Stud. 38, 692–700. https://doi.org/10.1111/ijcs.12142.
Hake, J.F., Schlör, H., Schürmann, K., Venghaus, S., 2016. Ethics, sustainability and the water, energy, food nexus approach - a new integrated assessment of urban systems. In: Energy Procedia. Elsevier Ltd, pp. 236–242. https://doi.org/10.1016/j.egypro.2016.06.155.
Heck, V., Hoff, H., Wirsenius, S., Meyer, C., Kreft, H., 2018. Land use options for staying within the Planetary Boundaries – synergies and trade-offs between global and local sustainability goals. Global Environ. Change 49. https://doi.org/10.1016/j.gloenvcha.2018.02.004.
Hoekstra, A.Y., Wiedmann, T.O., 2014. Humanity's unsustainable environmental footprint. Science 344 (80), 1114–1117. https://doi.org/10.1126/science.1248365.
Hoff, H., Döll, P., Fader, M., Gerten, D., Hauser, S., Siebert, S., 2014. Water footprints of cities-indicators for sustainable consumption and production. Hydrol. Earth Syst. Sci. 18, 213–226. https://doi.org/10.5194/hess-18-213-2014.
Hoornweg, D., Hosseini, M., Kennedy, C., Behdadi, A., 2016. An urban approach to planetary boundaries. Ambio 45, 567–580. https://doi.org/10.1007/s13280-016-0764-y.
Hughes, S., Giest, S., Tozer, L., 2020. Accountability and data-driven urban climate governance. Nat. Clim. Change 10 (12), 1085–1090. https://doi.org/10.1038/s41558-020-00953-z.
Huovila, A., Bosch, P., Airaksinen, M., 2019. Comparative analysis of standardized indicators for Smart sustainable cities: what indicators and standards to use and when? Cities 89, 141–153. https://doi.org/10.1016/j.cities.2019.01.029.
IBEC, 2014. CASBEE for Urban Development Technical Manual, 2014 Edition. Institute for Building Environment and Energy Conservation, Tokyo, Japan.
International Council for Local Environment Initiatives, 2020. ICLEI - Local Governments for Sustainability. https://www.iclei.org/. (Accessed 18 November 2020).
International Standards Organisation, 2018. ISO 37120:2018 - Sustainable Cities and Communities — Indicators for City Services and Quality of Life.
Ipcc, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The changing metabolism of cities. J. Ind. Ecol. 11, 43–59. https://doi.org/10.1162/jie.2007.1107.
Kennedy, C., Stewart, I.D., Ibrahim, N., Facchini, A., Mele, R., 2014. Developing a multi-layered indicator set for urban metabolism studies in megacities. Ecol. Indicat. 47, 7–15. https://doi.org/10.1016/j.ecolind.2014.07.039.
Kubiszewski, I., Zakariyya, N., Costanza, R., 2018. Objective and subjective indicators of life satisfaction in Australia: how well do people perceive what supports a good life? Ecol. Econ. 154, 361–372. https://doi.org/10.1016/j.ecolecon.2018.08.017.
Kumar, S., Santara, A., Banerji, H., 2020. Pentagram sustainability model. Int. Rev. Spat. Plan. Sustain. Dev. 8, 100–117. https://doi.org/10.14246/irspsda.8.2_100.
Laslett, D., Urmee, T., 2020. The effect of aggregation on city sustainability rankings. Ecol. Econ. 112 https://doi.org/10.1016/j.ecolind.2020.106076.
Lenzen, M., Peters, G.M., 2010. How City dwellers affect their resource Hinterland. J. Ind. Ecol. 14, 73–90. https://doi.org/10.1111/j.1530-9290.2009.00190.x.
Lenzen, M., Li, M., Malik, A., Pomponi, F., Sun, Y.-Y., Wiedmann, T., Faturay, F., Fry, J., Gallego, B., Geschke, A., Gómez-Paredes, J., Kanemoto, K., Kenway, S., Nansai, K., Prokopenko, M., Wakiyama, T., Wang, Y., Yousefzadeh, M., 2020. Global socio-economic losses and environmental gains from the Coronavirus pandemic. PloS One 15, e0235654. https://doi.org/10.1371/journal.pone.0235654.
Li, M., Wiedmann, T., Liu, J., Wang, Y., Hu, Y., Zhang, Z., Hadjikakou, M., 2020. Exploring consumption-based planetary boundary indicators: an absolute water footprinting assessment of Chinese provinces and cities. Water Res. 184, 116163. https://doi.org/10.1016/j.watres.2020.116163.
Li, M., Wiedmann, T., Fang, K., Hadjikakou, M., 2021. The role of planetary boundaries in assessing absolute environmental sustainability across scales. Environ. Int. 152 https://doi.org/10.1016/j.envint.2021.106475.
Lu, Y., Chen, B., 2017. Urban ecological footprint prediction based on the Markov chain. J. Clean. Prod. 163, 146–153. https://doi.org/10.1016/j.jclepro.2016.03.034.
Lucas, Paul, Wilting, Harry, 2018. Using planetary boundaries to support national implementation of environment-related Sustainable Development Goals. PBL Netherlands Environ. Assess. Agency, The Hague, 2748.
Maranghi, S., Parisi, M.L., Facchini, A., Rubino, A., Kordas, O., Basosi, R., 2020. Integrating urban metabolism and life cycle assessment to analyse urban sustainability. Ecol. Indicat. 112, 106074. https://doi.org/10.1016/j.ecolind.2020.106074.
Marvin, S., Luque-Ayala, A., McFarlane, C., 2015. Smart Urbanism : Utopian Vision or False Dawn? Routledge, London, UK.
Maslow, A.H., 1943. A theory of human motivation. Psychol. Rev. 50, 370–396.
Massaro, E., Athanassiadis, A., Psyllidis, A., Binder, C.R., 2020. Ontology-based integration of urban sustainability indicators. In: Binder, C.R., Wyss, R., Massaro, E. (Eds.), Sustainability Assessment of Urban Systems. Cambridge University Press. https://doi.org/10.1017/9781108574334.
Matuštík, J., Kočí, V., 2021. What is a footprint? A conceptual analysis of environmental footprint indicators. J. Clean. Prod. 285 https://doi.org/10.1016/j.jclepro.2020.124833, 124833.
Max-neef, M.a., Hopenhayn, M., Hamrell, S., 1992. Human Scale Development: Conception, Application and Further Reflections, vol. 1. The Apex Press, New York and London.
Medina, L., Schneider, F., 2018. IMF working paper 18/17 shadow economies around the world: what did we learn over the last 20 Years? International Monetary Fund.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600. https://doi.org/10.5194/hess-15-1577-2011.
Merino-Saum, A., Halla, P., Superti, V., Boesch, A., Binder, C.R., 2020. Indicators for urban sustainability: key lessons from a systematic analysis of 67 measurement initiatives. Ecol. Indicat. 119, 106879. https://doi.org/10.1016/j.ecolind.2020.106879.
Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., Oswald, Y., 2020. Providing decent living with minimum energy: a global scenario. Global Environ. Change 65. https://doi.org/10.1016/j.gloenvcha.2020.102168.
Minx, J.C., Creutzig, F., Medinger, V., Ziegler, T., 2011. Developing a Pragmatic Approach to Assess Urban Metabolism in Europe: A Report to the. European Environment Agency.
Mirabella, N., Allacker, K., Sala, S., 2019. Current trends and limitations of life cycle assessment applied to the urban scale: critical analysis and review of selected literature. Int. J. Life Cycle Assess. 24, 1174–1193. https://doi.org/10.1007/s11367-018-1467-3.
Mischen, P., Homsy, G., Lipo, C., Holahan, R., Imbruce, V., Pape, A., Zhu, W., Graney, J., Zhang, Z., Holmes, L., Reina, M., 2019. A foundation for measuring community sustainability. Sustainability 11, 1903. https://doi.org/10.3390/su11071903.
Moran, D., Kanemoto, K., Jiborn, M., Wood, R., Többen, J., Seto, K.C., 2018. Carbon footprints of 13 000 cities. Environ. Res. Lett. 13 https://doi.org/10.1088/1748-9326/aac72a.
Morris, Z.B., Weissburg, M., Bras, B., 2020. Ecological network analysis of urban–industrial ecosystems. J. Ind. Ecol. 25 (1), 193–204. https://doi.org/10.1111/jiec.13043.
Musango, J.K., Currie, P., Robinson, B., 2017. Urban metabolism for resource-efficient cities. Paris UN Environ 1–40.
Naidu, R., Biswas, B., Willett, I.R., Cribb, J., Kumar Singh, B., Paul Nathanail, C., Coulon, F., Semple, K.T., Jones, K.C., Barclay, A., John Aitken, R., 2021. Chemical pollution: a growing peril and potential catastrophic risk to humanity. Environ. Int. 156, 106616. https://doi.org/10.1016/j.envint.2021.106616.
Newton, P.W., 2012. Liveable and sustainable? Socio-technical challenges for twenty-first-century cities. J. Urban Technol. 19, 81–102. https://doi.org/10.1080/10630732.2012.626703.
Ottelin, J., Ala-Mantila, S., Heinonen, J., Wiedmann, T., Clarke, J., Junnila, S., 2019. What can we learn from consumption-based carbon footprints at different spatial scales? Review of policy implications. Environ. Res. Lett. 14, 093001 https://doi.org/10.1088/1748-9326/ab2212.
Ottelin, J., Cetinay, H., Behrens, P., 2020. Rebound effects may jeopardize the resource savings of circular consumption: evidence from household material footprints. Environ. Res. Lett. 15 (10) https://doi.org/10.1088/1748-9326/abaa78.
O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1, 88–95. https://doi.org/10.1038/s41893-018-0021-4.
Patterson, M., McDonald, G., Hardy, D., 2017. Is there more in common than we think? Convergence of ecological footprinting, emergy analysis, life cycle assessment and other methods of environmental accounting. Ecol. Model. 362, 19–36. https://doi.org/10.1016/j.ecolmodel.2017.07.022.
Pautasso, M., 2007. Scale dependence of the correlation between human population presence and vertebrate and plant species richness. Ecol. Lett. 10, 16–24. https://doi.org/10.1111/j.1461-0248.2006.00993.x.
Pedro, J., Reis, A., Duarte Pinheiro, M., Silva, C., 2019. A systematic review of the international assessment systems for urban sustainability. In: IOP Conference Series: Earth and Environmental Science. https://doi.org/10.1088/1755-1315/323/1/012076.
Persson, L., Arvidsson, R., Berglund, M., Cederberg, C., Finnveden, G., Palm, V., Sörme, L., Schmidt, S., Wood, R., 2019. Indicators for national consumption-based accounting of chemicals. J. Clean. Prod. 215, 1–12. https://doi.org/10.1016/j.jclepro.2018.12.294.
Ramaswami, A., Russell, A.G., Culligan, P.J., Rahul Sharma, K., Kumar, E., 2016. Meta-principles for developing smart, sustainable, and healthy cities. Science 80. https://doi.org/10.1126/science.aaf7160.
Ramaswami, A., Tong, K., Canadell G., J., Jackson B., R., Stokes, E. (Kellie), Dhakal, S., Finch, M., Jittrapirom, P., Singh, N., Yamagata, Y., Yewdall, E., Yona, L., Seto C., K., 2021. Carbon analytics for net-zero emissions sustainable cities. Nat. Sustain. 4, 460–463. https://doi.org/10.1038/s41893-021-00715-5.
Raworth, K., 2012. A safe and just space for humanity: can we live within the doughnut? Oxfam discussion papers. Oxfam Policy Pract. Clim. Chang. Resil. 8, 1–26. https://doi.org/10.1080/00420980120087081.
Raworth, K., 2017. Doughnut Economics. 7 Ways to Think like a 21st Century Economist. Chelsea Green Publ., Vermont.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C.C., Joachim, H., Schnellhuber, Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H.H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.K.A., Schellnhuber, H. J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H.H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.K.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.
Ryberg, M.W., Andersen, M.M., Owsianiak, M., Hauschild, M.Z., 2020. Downscaling the Planetary Boundaries in absolute environmental sustainability assessments – a review. J. Clean. Prod. 123287 https://doi.org/10.1016/j.jclepro.2020.123287.
Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., Rockström, J., 2019. Six transformations to achieve the sustainable development goals. Nat. Sustain. 2, 805–814. https://doi.org/10.1038/s41893-019-0352-9.
Sala, S., Goralczyk, M., 2013. Chemical footprint: a methodological framework for bridging life cycle assessment and planetary boundaries for chemical pollution. Integrated Environ. Assess. Manag. 9, 623–632. https://doi.org/10.1002/ieam.1471.
Sala, S., Ciuffo, B., Nijkamp, P., 2015. A systemic framework for sustainability assessment. Ecol. Econ. 119, 314–325. https://doi.org/10.1016/j.ecolecon.2015.09.015.
Saltelli, A., Benini, L., Funtowicz, S., Giampietro, M., Kaiser, M., Reinert, E., Van Der Sluijs, J.P., 2020. The technique is never neutral. How methodological choices condition the generation of narratives for sustainability. Environ. Sci. Pol. 106, 87–98. https://doi.org/10.1016/j.envsci.2020.01.008.
Schreiber, C.E., 2016. Water Use Patterns : Examining the Impact of Population Density on Municipal Drought Response. University of Texas, Austin.
Schröder, P., Vergragt, P., Brown, H.S., Dendler, L., Gorenflo, N., Matus, K., Quist, J., Rupprecht, C.D.D., Tukker, A., Wennersten, R., 2019. Advancing sustainable consumption and production in cities - a transdisciplinary research and stakeholder engagement framework to address consumption-based emissions and impacts. J. Clean. Prod. 213, 114–125. https://doi.org/10.1016/j.jclepro.2018.12.050.
Seto, K.C., Golden, J.S., Alberti, M., Turner, B.L., 2017. Sustainability in an urbanizing planet. Proc. Natl. Acad. Sci. U. S. A 114 (34), 8935–8938. https://doi.org/10.1073/pnas.1606037114.
Sharifi, A., 2019. A critical review of selected smart city assessment tools and indicator sets. J. Clean. Prod. 233, 1269–1283. https://doi.org/10.1016/j.jclepro.2019.06.172.
Sharifi, A., 2020. A typology of smart city assessment tools and indicator sets. Sustain. Cities Soc. 53 https://doi.org/10.1016/j.scs.2019.101936.
Sharifi, A., Murayama, A., 2015. Viability of using global standards for neighbourhood sustainability assessment: insights from a comparative case study. J. Environ. Plann. Manag. 58, 1–23. https://doi.org/10.1080/09640568.2013.866077.
Shmelev, S.E., Shmeleva, I.A., 2019. Multidimensional sustainability benchmarking for smart megacities. Cities 92, 134–163. https://doi.org/10.1016/j.cities.2019.03.015.

Song, Y., van Timmeren, A., Wandl, A., 2019. A literature review and categorisation of sustainability-aimed urban metabolism indicators: a context, indicator, mechanism, outcome analysis. Reg. Stat. 9, 54–71. https://doi.org/10.15196/rs090103.
Sorrell, S., Gatersleben, B., Druckman, A., 2020. The limits of energy sufficiency: a review of the evidence for rebound effects and negative spillovers from behavioural change. Energy Res. Soc. Sci. 64, 101439 https://doi.org/10.1016/j.erss.2020.101439.
S.T.A.R. Communities, 2016. STAR Community Rating System Version 2.0. STAR Communities, Washington, DC.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science (80-.) 347. https://doi.org/10.1126/science.1259855, 1259855–1259855.
Sterner, T., Barbier, E.B., Bateman, I., van den Bijgaart, I., Crépin, A.S., Edenhofer, O., Fischer, C., Habla, W., Hassler, J., Johansson-Stenman, O., Lange, A., Polasky, S., Rockström, J., Smith, H.G., Steffen, W., Wagner, G., Wilen, J.E., Alpízar, F., Azar, C., Carless, D., Chávez, C., Coria, J., Engström, G., Jagers, S.C., Köhlin, G., Löfgren, Å., Pleijel, H., Robinson, A., 2019. Policy design for the anthropocene. Nat. Sustain. 2, 14–21. https://doi.org/10.1038/s41893-018-0194-x.
Sudmant, A., Gouldson, A., Millward-Hopkins, J., Scott, K., Barrett, J., 2018. Producer cities and consumer cities: using production- and consumption-based carbon accounts to guide climate action in China, the UK, and the US. J. Clean. Prod. 176, 654–662. https://doi.org/10.1016/j.jclepro.2017.12.139.
Suganthi, L., 2018. Multi expert and multi criteria evaluation of sectoral investments for sustainable development: an integrated fuzzy AHP, VIKOR/DEA methodology. Sustain. Cities Soc. 43, 144–156. https://doi.org/10.1016/j.scs.2018.08.022.
Teh, S.H., Wiedmann, T., Moore, S., 2018. Mixed-unit hybrid life cycle assessment applied to the recycling of construction materials. J. Econ. Struct. 7, 1–25. https://doi.org/10.1186/s40008-018-0112-4.
The Mori Memorial Foundation, 2019. Global Power City Index 2019 Summary.
Thomson, G., Newman, P., 2018. Urban fabrics and urban metabolism – from sustainable to regenerative cities. Resour. Conserv. Recycl. 132, 218–229. https://doi.org/10.1016/j.resconrec.2017.01.010.
Thriving Cities Initiative, 2020. Creating City Portraits: A methodological guide from The Thriving Cities Initiative. A report by Doughnut Economy Action Lab, Biomimicry 3.8, C40 Cities. Circle Economy and KR Foundation.
Turcu, C., 2013. Re-thinking sustainability indicators: local perspectives of urban sustainability. J. Environ. Plann. Manag. 56, 695–719. https://doi.org/10.1080/09640568.2012.698984.
UN, 2018. The World 's Cities in 2018-Data Booklet. Department of Economic and Social Affairs, Population Division, United Nations (ST/ESA/SER.A/417).
UN Habitat, 2004. Urban Indicators Guidelines: Monitoring the Habitat Agenda and the Millennium Development Goals. UN-Habitat.
UN Habitat, 2016. Measurement of City Prosperity: Methodology and Metadata. UN-Habitat.
United Nations Statistics Division, 2016. SDG indicators. UN chron. https://doi.org/10.18356/0aec43e1-en.
USGBC, 2018. LEED V4 for Neighborhood Development. U.S. Green Building Council.
USGBC, 2020. LEED v4.1 for Cities and Communities. U.S. Green Building Council.
Vanham, D., Leip, A., Galli, A., Kastner, T., Bruckner, M., Uwizeye, A., van Dijk, K., Ercin, E., Dalin, C., Brandão, M., Bastianoni, S., Fang, K., Leach, A., Chapagain, A., Van der Velde, M., Sala, S., Pant, R., Mancini, L., Monforti-Ferrario, F., Carmona-Garcia, G., Marques, A., Weiss, F., Hoekstra, A.Y., 2019. Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. Sci. Total Environ. 693, 133642. https://doi.org/10.1016/j.scitotenv.2019.133642.
Vea, E.B., Ryberg, M., Richardson, K., Hauschild, M.Z., 2020. Framework to define environmental sustainability boundaries and a review of current approaches. Environ. Res. Lett. 15 (10), 103003 https://doi.org/10.1088/1748-9326/abac77.
Verma, P., Raghubanshi, A.S., 2018. Urban sustainability indicators: challenges and opportunities. Ecol. Indicat. 93, 282–291. https://doi.org/10.1016/j.ecolind.2018.05.007.
Vita, G., Hertwich, E.G., Stadler, K., Wood, R., 2019. Connecting global emissions to fundamental human needs and their satisfaction. Environ. Res. Lett. 14 https://doi.org/10.1088/1748-9326/aae6e0.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11 (5), 314–321. https://doi.org/10.1038/s41561-018-0113-9.
Wiedmann, Tommy, Allen, Cameron, 2021. City footprints and SDGs provide untapped potential for assessing city sustainability. Nat. Commun. 12, 3758 https://doi.org/10.1038/s41467-021-23968-2.
Wiedmann, T., Chen, G., Owen, A., Lenzen, M., Doust, M., Barrett, J., Steele, K., 2021. Three-scope carbon emission inventories of global cities. Journal of Industrial Ecology 25 (3), 735–750. https://doi.org/10.1111/jiec.13063.
Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nat. Commun. 11, 3107. https://doi.org/10.1038/s41467-020-16941-y.
Xiao, Y., Norris, C.B., Lenzen, M., Norris, G., Murray, J., 2017. How social footprints of Nations can assist in achieving the sustainable development goals. Ecol. Econ. 135, 55–65. https://doi.org/10.1016/j.ecolecon.2016.12.003.
Xiao, Y., Lenzen, M., Benoît-Norris, C., Norris, G.A., Murray, J., Malik, A., 2018. The corruption footprints of Nations. J. Ind. Ecol. 22, 68–78. https://doi.org/10.1111/jiec.12537.
Yigitcanlar, T., Kamruzzaman, M., 2018. Does smart city policy lead to sustainability of cities? Land Use Pol. 73, 49–58. https://doi.org/10.1016/j.landusepol.2018.01.034.
Zhang, Y., Yang, Z., Yu, X., 2015. Urban metabolism: a review of current knowledge and directions for future study. Environ. Sci. Technol. 49, 11247–11263. https://doi.org/10.1021/acs.est.5b03060.
Zinkernagel, R., Evans, J., Neij, L., 2018. Applying the SDGs to cities: business as usual or a new dawn? Sustain. Times 10, 3201. https://doi.org/10.3390/su10093201.