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REPORT

# An urban approach to planetary boundaries

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**Abstract** The achievement of global sustainable development goals subject to planetary boundaries will mostly be determined by cities as they drive cultures, economies, material use, and waste generation. Locally relevant, applied and quantitative methodologies are critical to capture the complexity of urban infrastructure systems, global inter-connections, and to monitor local and global progress toward sustainability. An urban monitoring (and communications) tool is presented here illustrating that a city-based approach to sustainable development is possible. Following efforts to define and quantify safe planetary boundaries in areas such as climate change, biosphere integrity, and freshwater use, this paper modifies the methodology to propose boundaries from a city's perspective. Socio-economic boundaries, or targets, largely derived from the Sustainable Development Goals are added to bio-physical boundaries. Issues such as data availability, city priorities, and ease of implementation are considered. The framework is trialed for Toronto, Shanghai, Sao Paulo, Mumbai, and Dakar, as well as aggregated for the world's larger cities. The methodology provides an important tool for cities to play a more fulsome and active role in global sustainable development.

**Keywords** Sustainability · Planetary boundaries · Bio-physical and socio-economic limits · Urbanization · Cities

## INTRODUCTION

Sustainable development requires adequate standards of living for current and future generations while living within the planet's carrying capacity (Dearing et al. 2014). Through use of natural resources, aided by scientific discovery and technological innovation, humans have evolved to predominantly live in urban environments. Cities are now home to some 55 % of global population, likely to be 66 % by 2050 (UN 2014). Residents of cities are significant drivers of environmental degradation, e.g., city residents are responsible for about 80 % of global greenhouse gas emissions (Hoornweg et al. 2011), and a similar share of GDP in the global economy; thus city-residents purchase the bulk of threatened and endangered species. Cities can also be more acutely impacted by global trends, e.g., the impact of rising commodity prices, food security, and climate change. Many international treaties negotiated by national governments are by-and-large undertaken on behalf of their respective cities, or potential customers in international cities. Thus, the characteristics and designs of cities are central to sustainable development (Bettencourt and West 2010; Banister 2012; Ahern 2013).

In recent years, there is increasing interest in sustainable development, assessment of which requires quantification of both bio-physical environmental boundaries and social conditions. Rockstrom et al. (2009) initially proposed a suite of planetary system boundaries. The approach provides a relatively simple, easily understood, 'snapshot' of progress toward bio-physical limits. Steffen et al. (2015) updated the framework, adjusting current values and better defining zones of uncertainty. The planetary boundaries are refined as climate change, novel entities (e.g., new substances such as heavy metals and modified life forms—not yet quantified), ozone depletion, aerosol loading (not yet

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quantified), ocean acidification, biogeochemical flows (nitrogen and phosphorous), freshwater use, land-system change, and biosphere integrity (genetic and, not yet quantified, functional diversity).

Building on the bio-physical boundaries of Rockstrom et al. (2009) and Steffen et al. (2015) and the socio-economic approach by Raworth (2012) Dearing et al. (2014) propose a 'safe and just operating space for human well-being,' that includes both physical and social boundaries. While Dearing et al. (2014) indicators provide insights into a region's social-ecological state, other important aspects of basic urban services, such as transportation, security and safety, geophysical risks, and biodiversity are also needed, particularly if long-term involvement of cities is sought.

In an attempt to develop 'contours of a resilient global future,' Gerst et al. (2013) combined scenario analysis (to 2100), planetary boundaries, and targets for human development. Gerst et al. (2013) extend the initial physical boundaries assessment with the addition of hunger, inequity, and water stress. The analysis is at a global scale and supports long-term scenario planning and is sufficiently robust to accommodate dramatic social and technological change. The approach presented in this paper provides a way to view planetary and local boundaries as development targets from a metropolitan city perspective.

Planetary boundaries cannot be directly applied at a local level; however, cities as key drivers, and those most impacted by global influences, need to have proper attribution of emissions and impacts quantified. This challenge arose in attributing greenhouse gas emissions to corporations and sub-national governments. National inventories, for example, are solely production based, accounting for all activities within national borders. City residents and corporate customers are arguably also responsible for upstream emissions and impacts for production and transportation that occur outside their borders. ISO 14074 provides a methodology to comprehensively estimate all emissions from production to final use of a product, and is based on Scopes 1 (direct), 2 (indirect from purchased energy), and 3 (indirect, embodied, ISO 2006). A similar approach, quantifying direct and indirect (embodied) impacts, can be used to assess overall impacts of food production through growing use of irrigation water (Valipour et al. 2015), as well with nitrogen and phosphorous use and addressing the "degree of subjectivity in setting boundaries," and the need to capture differentiated application of boundaries, e.g., 'over-use' of fertilizer in China vs 'under-use' in Rwanda (Nordhaus et al. 2012).

Socio-economic boundaries similar to physical boundaries are derived from targets suggested through programs such as Millennium Development Goals and Sustainable Development Goals. These are mostly service level targets, e.g., percent of population with solid waste collection and electrical service, that influence quality of life globally or specifically within the analyzed city. Some researchers suggest upper limits for several of these targets, e.g., caloric intake, energy consumption, and GDP (Raworth 2012). The methodology presented in this paper uses boundaries without upper-bounds to facilitate easier comparison across cities and over time, and is consistent with several engineering approaches (Gnanapragasam et al. 2010; Rosen 2012).

In this paper, we explore the bio-physical and socio-economic boundaries within which cites can develop sustainably. The main objectives of this paper are to introduce city-level contributions to, and impacts from bio-physical and socio-economic boundaries and to demonstrate a framework for comparing the performance of a city or urban agglomeration against global boundaries and the Sustainable Development Goals (SDG 2015). The methodology is developed as a way to enable cities to more fully participate in global efforts toward sustainability, as well as to monitor relative local progress and concerns.

The methodology builds on the well-known planetary boundaries approach of Rockstrom et al. (2009), updated by Steffen et al. (2015), and proposes bio-physical and socio-economic boundaries, based largely on the Millennium Development Goals, supplanted by the Sustainable Development Goals (UN 2013 and 2015). The socio-economic boundaries are derived based on credible data, e.g., from World Council on City Data, coverage of global sustainability objectives, and extensive discussions with stakeholders and city representatives (Hoornweg and Freire 2013). They include: youth opportunity, economy, access to energy and energy intensity, mobility and connectivity, institutions, basic services, and security and public safety. The socio-economic limits are aggregated globally (for the world's largest cities).

The contribution of this paper is primarily methodological framework, but we also provide example results for five representative large cities. In the methodology, we describe approaches for attribution of bio-physical and socio-economic planetary boundaries limits at the city-scale, as well as discussing how to determine the performance of cities against these boundaries. Results are presented for the metropolitan areas of Toronto, Sao Paulo, Shanghai, Mumbai, and Dakar. These five cities were selected for their regional representation, size (all will have more than 5 million residents by 2050), data availability, and mix of growth rates, e.g., Dakar and Mumbai are among the world's faster growing cities. The selected cities are also the largest in their respective country.

Where possible selected data sources are already collected by cities, e.g., ISO 37120 sustainable communities indicators, and potentially third-party verifiable. This is important for the investment and engineering communities who could then use the boundaries as input to urban infrastructure evaluation *vis a vis* sustainability targets.

We envisage that the methods described here will be refined and eventually applied to all larger cities across the world. Regular updating and consultations with residents will improve data estimates. The larger cities are defined as those expected to have 5 million or more residents by 2050—about 120 metro areas (Hoornweg and Pope 2013). These 'Future Five' cities are home to more than 20 % of the world's urban population and almost twice that in GDP. The methodology discussed in this paper would have greater utility once applied to all Future Five cities, and re-iterated on a regular basis.

Sustainable development and planetary boundaries are often presented as a global challenge. Rightly so, as broad issues such as climate change, loss of biodiversity, and stratospheric ozone depletion are global manifestations of unsustainable actions. However, the vast majority of the actions leading to these impacts originate in cities.

## MATERIALS AND METHODS

To capture the complexity and integrated nature of sustainable development a suite of 14 indicators are presented, some with multiple inputs and some that include estimated indices. The boundaries to these indicators (or limits) are roughly half physical and half socio-economic. A metropolitan-wide scale is used as a city's overall ecosystem and economic impact is driven by the entire urban agglomeration, i.e., the actions of all residents. Metropolitan scale programs in areas such as energy and transportation also offer the greatest opportunity to ameliorate system impacts (Hoornweg and Freire 2013).

The methodology has four main components described below:

- Determination of bio-physical planetary boundaries at the urban scale,
- Assessment of the performance of cities against these bio-physical boundaries,
- Determination of socio-economic boundaries at the urban scale, and
- Assessment of socio-economic boundaries based on local and national performance.

A city's data (for each indicator) are scaled against the relevant data for the global average (targets or limits where applicable—Table 1). A scale of one is given to the indicators for global average values. Indicators with a positive effect on the sustainability status of a city have an inverse relation with the global average. For example "access to clean energy for cooking" is an indicator of greater sustainability in a city. Currently nearly 88 % of urban areas have this access (Newman and Jennings 2008). If 100 % of a city's population has access to clean energy for cooking, the sustainability status (for the related indicator) is higher in that city than compared to the global average. Hence, the indicator scales less than one, and the value of that city remains below the global average (limits or targets). Indicators with negative impact on sustainability, e.g., GHG emissions, are assigned a scale greater than one. For example, Toronto's GHG emissions level of 11.5 $tCO_2$/cap/year (for the metropolitan region, excluding scope 3 emissions) is higher than the global average of 4.7 $tCO_2$/cap/year. Therefore, the related indicator is higher and exceeds the scale of one for the global average. The figures also can be used to compare the five cities to each other. These comparisons and targets enable a city-assessment of sustainable development locally and globally. For example in the Toronto metro area per-capita residential GHG emissions can vary 60 % across neighborhoods (Kennedy et al. 2011).

### Global Bio-physical boundaries

Building upon Rockstrom et al. and Steffen et al. boundaries (i.e., limits), Fig. 1 and Table 2 present a global aggregate for proposed bio-physical boundaries of the world's largest cities. The approach is simplified from the current nine planetary boundaries as described here.

'Pollution' is added as a city-specific indicator to estimate local (and cumulative) values for air pollution (smog and indoor/outdoor particulate matter), water pollution (COD, BOD, flotsam, and heavy metals), and land pollution (solid waste and brownfields). This pollution may have both local and global impacts. For example, solid waste discharges to oceans (plastics), black carbon, and trace organics from waste combustion. A future refinement of the methodology will include global compilation for (local) pollution that impacts at both the local and global scale, e.g., smog, trace organics, black carbon. The boundaries are presented as an average for the overall urban area, even though pollution levels can vary markedly within a city. Pollution is presented as a hybrid boundary, reflecting the complexity and inter-connectedness of local air pollution in large cities of China and India where, for example, any global effort to reduce GHG emissions will need to be developed in concert with local air quality improvement.

The methodology includes an additional boundary for geophysical risk. This reflects mainly the extrinsic aspects of seismic, erosional, and weather-related risk that the city faces, e.g., sea level rise, earthquake, volcanoes, landslides, storms, and flooding. The value is an aggregate estimate of risk to life and property. Geophysical risk includes rapid onset events such as typhoons and earthquakes: Long-term

**Table 1** Information sources for city assessments

| Data sources for city assessments | |
|---|---|
| Bio-physical science indicators | |
| Climate change | GHG emissions per capita (Scopes 1, 2 and [eventually] 3; C40-ICLEI-WRI GPC, GCI-C and SDG)[a] |
| Rate of biodiversity loss | Ecological footprint (WWF Living Planet Report 2014); Index of biodiversity impact (SDG—TBD) |
| Fresh water use | Percent of city with potable water supply (GCI-C); Total per capita water consumption (GCI-S, SDG); index of embodied water consumption (SDG—TBD) |
| Change in land-use | Local land-use change in Ha (SDG—TBD); index of global land-use impact (embodied; SDG—TBD) |
| Nitrogen cycle | Per capita values as percent of global values based on estimated consumption patterns |
| Pollution | PM 2.5 (GCI-C); PM 10 (GCI-C); O3 (ozone—GCI-S); percent of city population with regular solid waste collection (GCI-C); percentage of city's wastewater receiving no treatment (GCI-C) |
| Geophysical risk | Number of natural disaster related deaths per 100,000 population (GCI-C); resilience of city (SDG—TBD); life and property casualty (by insurance payment—TBD) |
| Socio-economic indicators | |
| Youth opportunity | Under 5 mortality (SDG, GCI-C); Gender equity (SDG); percent female in schools (GCI-C); youth unemployment rate (GCI-S); average life expectancy (GCI-C) |
| Economy | Unemployment rate (GCI-C); Gini coefficient (SDG); percentage of population living in slums (GCI-C, SDG); local GDP (TBD) |
| Energy access and intensity | Percentage of city with authorized electrical service (SDG-C); energy intensity (SDG and partial GCI-S) |
| Mobility and connectivity | Annual number of public transport trips per capita (GCI-C); number of personal automobiles per capita (GCI-C); percentage of commuters using a travel mode other than a personal vehicle to work (GCI-S); commercial air connectivity (GCI-S); transportation fatalities per 100 000 population (GCI-S); number of internet connections per 100 000 population (GCI-C); index of connectivity (TBD) |
| Institutions | 'Ease of doing business'—World Bank (downscaled from country to city level); number of convictions for corruption by city officials per 100 000 population (GCI-S); tax collected as a percent of tax billed (GCI-S); debt service ratio (GCI-C) |
| Basic services | Percentage of population with regular solid waste collection (GCI-C); percentage of city population served by wastewater collection (GCI-C); percentage of population served with potable water supply (GCI-C); percent of houses flooded, per year (SDG—TBD) |
| Security and public safety | Number of fire-related deaths per 100 000 population (GCI-C); number of homicides per 100 000 population (GCI-C); violent crime rate per 100 000 population (GCI-C) |

[a] GCI-C and S, global city indicator 'core' and 'supporting' as defined in ISO 37120; SDG—sustainable development goals, 2015; TBD—to be developed. Where values are not yet available through GCI (WCCD) estimates are made by authors from existing data sources (to be updated as more data become available)

climate-related events, such as drought, pestilence, and changes to growing seasons are considered elsewhere. The values encompass overall 'urban resilience' (a function of risk and adaptive capacity). Urban resilience is an approach consistent with the casualty insurance industry and the ISO 37121 standard now under development (ISO 2014). The pollution and geophysical indicators addresses the common city response to global ecosystem impacts that derive from both local and global pollution (Grimm et al. 2008). The indicators meet the demands of city-based data availability (Table 1), consistency with published global planetary boundaries, and city priorities as reflected in the Sustainable Development Goals.

The limits are applicable to all cities; however larger cities are prioritized in this analysis, i.e., those cities (urban agglomerations) expected to have populations over 5 million by 2050. Values are presented as per capita (average for all city-residents).

The boundaries for climate change are common with current planetary boundaries (a total city-wide per capita GHG emissions value is used—using Scopes 1, 2 and where available, 3, WRI and WBCSD 2011a, b). Nitrogen values are also absolute per capita values. Fresh water use and land-use change are common with planetary boundaries and apportioned to individual cities.

A biodiversity index is needed to account for vicarious impacts a city-dweller may have on biodiversity, e.g., buying products from endangered species. Biodiversity (globally) is consistent with the genetic diversity measure of biosphere integrity in current planetary boundaries, however to facilitate differentiation at a city-level, the boundary contains a global estimate, based on WWF's

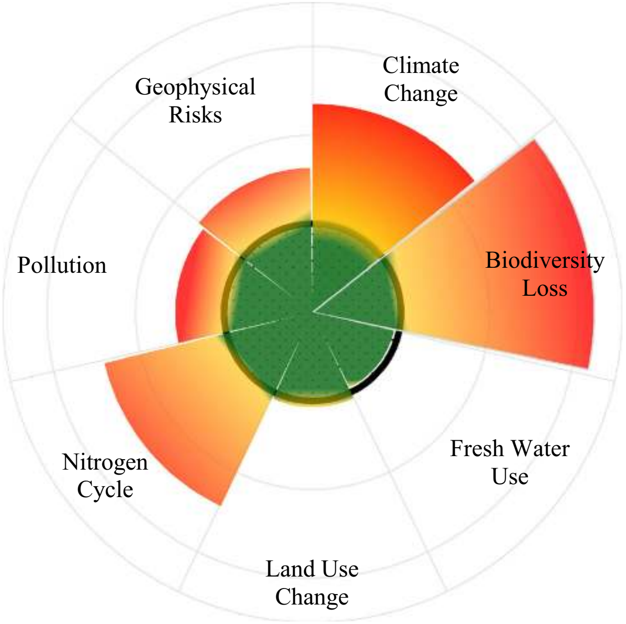

**Fig. 1** Bio-physical indicators for cities in a global context

'ecological footprint' (WWF 2014) (applied at a country-level), plus a city-specific 'index of biodiversity impact' (Table 3). Similar to the index of biodiversity impact, indices are also used for embodied water consumption and global land-use (see "Assessing bio-physical performance at the city-level" section).

Modifications to the global bio-physical planetary boundaries approach reflect city-based priorities and capacities (Fig. 1). Changes include: Atmospheric aerosol loading is omitted (atmospheric limits included in 'pollution' indicator); Ocean acidification is omitted (presumed to be included in climate change indicator); Climate change presented as aggregate GHG emissions by city, i.e., Scopes 1, 2 and where available 3; Biosphere integrity (as genetic diversity) is estimated for local and global activities deriving from city residents—two metrics used, one for local impacts on neighboring ecosystems and species, and a global index of biodiversity impact; Fresh water use is similar to GHG emissions, estimated as a local and global aggregate usage; Land-system change includes local and global activities; 'Pollution' is intended to capture particulate matter, smog, oxygen demand, turbidity, solid waste, and heavy metal contamination generated inside and outside the urban boundary, but directly impacting the city (including, eventually, most 'novel entities'); Nitrogen is estimated from consumption of food and horticultural products, plus relevant industrial activities (phosphorous to be added later—nitrogen considered the first priority, although phosphorous loading of local water courses severe in some cities); Geophysical risks are estimated for each urban area. Risk is residual (geophysical and climate risk) and aggregate (estimated against life and property for entire urban area). Data sources for the seven proposed cities-based physical indicators are presented in Table 1.

## Assessing bio-physical performance at the city-level

Many researchers have refined ways to apportion contributions to ecosystem degradation and potential impacts to cities, relative to countries (Dahl 2012; Duren and Miller 2012; Bechtel and Scheve 2013). Greenhouse gas emissions provide a useful precedent. Recognizing the need for a corporate inventory of GHG emissions that reflects direct and vicarious or embodied emissions (generated on behalf of the entity but done so through a third party, or in another area) the World Business Council for Sustainable Development (WBCSD) and World Resources Institute (WRI) began in 1997 to work together to develop a standard methodology consistent with national GHG inventories (WRI and WBCSD 2011a). 'Scopes 1,' '2,' and '3' were defined to account for where the emissions were generated while ensuring globally consistent national, local and corporate emissions inventories. This ensured consistent regional corporate and national inventories of GHG emissions. In 2006, the International Organization for Standardization (ISO) adopted the WRI-WBCSD Corporate Standard as the basis for ISO 14064-I: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals.

The initial work by WRI-WBCSD (and ISO 14064) (WRI and WBCSD 2011a), efforts by researchers (Kennedy et al. 2011), the World Bank (2010), and a common global protocol by C40-ICLEI-WRI led to a city-wide GHG emissions inventory now widely accepted and included within the recent ISO 37120 (ISO 2014). Cities are now able to credibly measure their GHG emissions, relative to national inventories (more than 100 cities have already done so). GHG emissions in Table 2 (t/cap/year) reflect the global protocol. As more scope 3 values are derived these numbers will more closely resemble national inventories.

The approach used for city-based emissions and consumption is similarly proposed for other physical indicators such as total water consumption (local and embodied); total nitrogen use; and land-use (local and embodied). For example the total land-use metric needs to reflect land converted locally as well as an estimate for land-use changes driven on behalf of the urban customer regardless of final point of sale. Four new indices are established for physical science indicators: index of biodiversity impact; index of embodied water consumption; index of global land-use; and urban resilience (Dahl 2012; Guha-Sapir and Hoyois 2013; ISO 2014). Similar to GHG emissions and Scope 3 contributions, the indices for biodiversity impact,

**Table 2** Bio-physical indicators, global current average

| Physical science indicators | Unit | Global (current) | Global (targets/ limits) | Source |
|---|---|---|---|---|
| Carbon dioxide emission | | | | |
| GHG emissions per capita | ($tCO_2$/cap. year) | 4.71 | 2 | Adapted from CCC (2014) |
| Rate of biodiversity loss | | | | |
| Ecological footprint | Global hectares demanded per capita | 2.6 | 1.9 | WWF Living Planet Report (2014) (down-scaled national values) |
| Index of biodiversity impact | Low-very high | Very high | Low | Estimated |
| Fresh water use | | | | |
| Total per capita water consumption[a] | L/cap/day | 989 | 1522 | Steffen et al. (2015) |
| Percent of city with potable water supply | % | 81 | 95* | Adapted from UNICEF-WHO (2012), *estimated value |
| Index of embodied water consumption (Litres) | Low-very high | Low | Low | Estimated |
| Change in land-use | | | | |
| Local land-use change (Ha) | Area of forested land as % of original forest cover | 65 | 75 | Steffen et al. (2015) |
| Population density | Person/km$^2$ | 3500 | TBD | Listed urban areas pop. density (Demographia 2006) |
| Index of global land-use impact (Ha) | Low-very high | Low | Low | Estimated |
| Nitrogen cycle | | | | |
| Per capita values as percent of global values based on estimated consumption patterns | kg-$N_2$/cap/year | 21 | 9 | Steffen et al. (2015) |
| Pollution | | | | |
| Percentage of city population with regular solid waste collection | % | 50 | 80* | Municipality Waste Management (MSW 2014), *estimated data |
| Percentage of city population served by wastewater collection | % | 76 | 80* | http://www.worldwaterweek.org/, * estimated data |
| PM 2.5; PM 10; O3 | μg/m$^3$ | 20 | 10 | World Health Organization (WHO) |
| Geophysical risk | | | | |
| Number of natural disaster related deaths | per 100 000 population | 0.134 | 0.09 | Adapted from (Guha-Sapir et al. 2013; Guha-Sapir and Hoyois 2013) |
| Percentage of GDP loss due to natural disasters | % | 0.2 | 0.1 | $143 Bn in 2012/UCL-WHO |
| Resilience of city | Low-very high | Medium | High | Estimated |

[a] This represents cumulative fresh water withdrawal from all sources. Cities usually report only their domestic water consumption; eventually embodied water consumption would be included, similar to GHG emissions inventories

* Estimated through SDG targets

embodied water consumption, and global land-use, and are mainly the embodied, or vicarious impact, associated with a product or service consumed by residents in the evaluated city. The index of urban resilience is estimated through the risks affecting the measured city added to the city's presumed adaptive capacity.

A similar approach is suggested to estimate a city's impact on biodiversity. The impact on local and transitory species is estimated, as is the city's estimated impact around the world. Therefore, cities whose citizens buy an inordinate amount of endangered animal parts for example, or purchase products grown on land cleared in sensitive habitats, would trend higher on the biodiversity index. Similarly, cities that have a disproportionate negative, or positive, impact on species habitat or migration, are denoted. Initially, these values are only estimated indicatively by the authors (Appendix S3); however, support from groups like World Wildlife Fund (WWF) and the World Bank, plus local engineering faculties, is anticipated as the indices are further refined.

The approach presented in this paper requires more than 44 data points for each evaluated city (calculations given in Appendix S4). Where necessary, the data are estimated for the urban agglomeration (metro area) either by aggregating

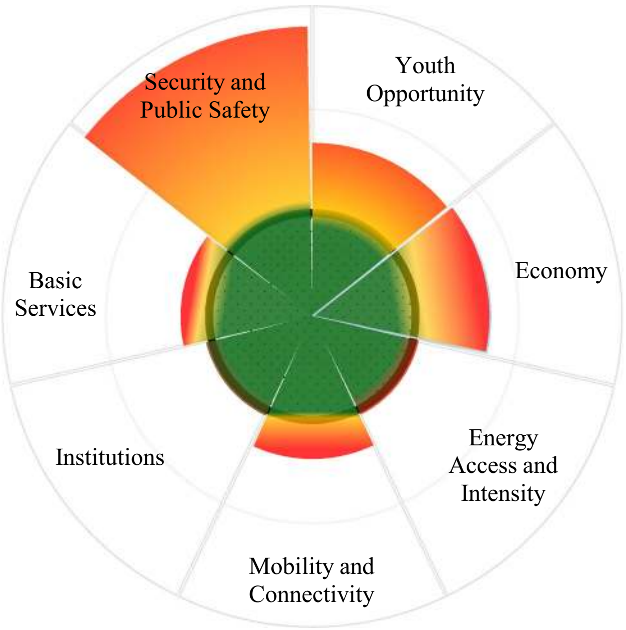

**Fig. 2** Socio-economic boundaries: global situation compared to targets

all local-government information, down-scaling per-capita national data, or using global average numbers (Tables 2, 4, and Appendices S1 and S2 provide sources of data). The quality of data varies—with some expected to be third-party verified, i.e., ISO 37120, and some initially estimated by the authors.

## Global socio-economic boundaries

The socio-economic limits, or boundaries, of sustainability also include seven metrics. Where definitive values are not available, values are estimated (and denoted). The boundaries are largely intrinsic capacities of a city and align with the Millennium Development Goals (MDG) and recent Sustainable Development Goals (SDG).

Figure 2 provides approximate global social boundaries (i.e., socio-economic)—estimated in relation to existing targets. Performance is based on the 24 indicators given in Table 4 (plus four yet to be determined). Within the seven limits, or boundaries, each indicator is given equal weighting. 'Youth opportunity' performance is based on under 5 mortality, gender equity, percentage of females in school, youth unemployment, life expectancy. Suggested targets are mainly a reflection of the MDGs (and recent SDGs). Most of the data are regularly available through data sets such as the Global City Indicators Facility (ISO 37120); however, approximations are needed as values are required for the entire urban area, rather than the individual city alone.

The proposed socio-economic boundaries are consistent with a hierarchy of sustainable cities and reflect discussions with more than 300 representative cities (Hoornweg and Freire 2013) and largely define the foundations of urban service delivery. Three to five indicative measures are used for each boundary. Youth opportunity includes metrics targeted to girls to reflect the critical nature of gender in economic growth (The World Bank 2011). In addition to per capita GDP (city-based) the economy boundary includes Gini coefficient and population in slums to capture general equity, as well as the overall city unemployment rate. Access to energy, and energy intensity, measure service provision, especially for the poor, and overall efficiency of energy use as measured through energy intensity (energy used per unit GDP). Mobility and connectivity are considered critical as urban economies are facilitated through personal interactions. The quality of institutions and security and public safety are particularly broad and challenging to capture across all cities. Indicative, and readily available, indicators are used initially, with possible augmentation as more data become available. Comprehensive education and health metrics are not used as these are often not the remit of the city and are often predicated on minimum quality of life and basic service delivery levels. Current values of the global social-science indicators are compared with target values (or boundaries—Tables 2 and 4).

## Assessing socio-economic performance at the city-level

Assessing socio-economic performance at individual city level is somewhat simpler than assessing corresponding bio-physical performance, once surrogate indicators are agreed. Much of the data are more readily available through use of down-scaled national values (consistent with the SDGs). Also, organizations, such as Global City Indicators Facility (and related World Council on City Data) will publish much of these data in standard ISO 37120 city-based format. Aggregation to metro-wide values is necessary. Unlike physical performance, no new indices are envisaged for monitoring of socio-economic performance. Over time, metrics such as 'mobility and connectivity' may need to be adjusted as indicators such as 'number of personal automobiles per capita' may not provide an accurate input to mobility performance.

Some socio-economic indicators such as GDP are given an upper-limit by researchers such as Raworth (2012). The methodology here however is based on targets consistent with the SDGs and therefore has no upper-bound.

## RESULTS

The bio-physical (and later socio-economic) indicators discussed above are evaluated for five world cities. These five cities were selected to meet regional representations, data availability and represent various rates of populations and economic growth. All cities are expected to be in the group of some 120 cities in 2050 expected to have populations above 5 million. A planning horizon of 35 years is envisaged as the methodological approach to boundaries presented in this paper might be applied to long-lived urban infrastructure. The cities and their populations are (Hoornweg and Pope 2013):

- Toronto (Greater Toronto Area, GTA): 6.3 million (2012); 7 million (2050)
- Sao Paulo (Metropolitan Region, SPMR): 21 million (2012); 22.8 million (2050)
- Shanghai (Metropolitan Area, SMA): 18.4 million (2012); 21.3 million (2050)
- Mumbai (Metropolitan Region, MMR): 18.8 million (2012); 42.4 million (2050)
- Dakar (Metropolitan Area, DMA): 2.8 million (2012); 8.5 million (2050).

### Bio-physical boundaries and performance

The seven bio-physical boundaries are scaled according to current global conditions (Table 3). Toronto and Shanghai are notable for their relatively high greenhouse gas emissions and fresh water use. The nitrogen values are estimated against global averages (Steffen et al. 2015) and a specific estimate of the city's energy and food consumption compared to the global average (and the corresponding increase/decrease in $N_2$). Mumbai has the highest levels of chemical pollution compared to the other four cities. An example of Mumbai's vulnerability to natural disasters was evident during the 2005 floods that affected many parts of the Maharashtra State, especially the Mumbai Metropolitan Area (Blackburn and Pelling 2014).

Appendix S1 provides detailed information on current city-based data for physical science indicators. The cities are also compared with current global averages, and the average of the five pilot cities. Transportation modes in Dakar are mainly public transit, walking, and biking, rather than personal automobiles which have the greatest share in Toronto and Shanghai. Nearly 90 % of Dakar's commuters use a travel mode other than personal vehicles (World Bank 2000).

Measuring the rate of biodiversity loss at a city level is challenging as both local and global impacts need to be quantified. Biodiversity is affected by many parameters and phenomena such as greenhouse gas emissions, land-use, water consumption, and nitrogen phosphorous cycles. Aside from Mumbai and Dakar, the other three cities have higher than (global) average biodiversity impacts reflecting their larger global purchasing power.

In Appendix S1, the highlighted cells represent estimated values based on current available data. The values are approximations intended to start an open-source iterative process. Ideally the values would be regularly updated, with a broader consensus, perhaps with support of local engineering faculties. Figure 3a (Bio-Physical Boundaries) highlights that the Toronto Area follows common traits of more affluent cities with a disproportionate contribution to climate change, nitrogen cycle, change in land-use, and fresh water consumption. Of the 44 838 species assessed in the IUCN 'Red List' (IUCN 2014), 16 928 are listed as threatened, of which 180 are local to Ontario, Canada, according to the Ministry of Natural Resources and Forestry. Canada's ecological footprint is used to estimate biodiversity loss in Toronto, as these numbers are reported at country scale in the WWF's 2014 Living Planet Report (WWF 2014). The same approach is used for the other four cities. Values are expected to be further refined with additional consideration for city-specific activities such as migratory bird loss in Toronto (high-rise tower strikes at night).

Sao Paulo is prone to landslides, lightening, and floods (de Brito Jr. et al. 2011). From 2005 to 2011, 37 casualties were reported annually in the City of Sao Paulo due to natural disasters, leading to 0.09 deaths per 100 000 inhabitants. This is less than the global annual average of 0.134 deaths per 100 000 inhabitants, according to a joint

**Table 3** Bio-physical indicators for the five example cities; global average normalized to 1

| Bio-physical Indicators | Toronto | Sao Paulo | Shanghai | Mumbai | Dakar |
|---|---|---|---|---|---|
| Carbon dioxide Emission | 2.4 | 0.3 | 2.5 | 0.6 | 0.2 |
| Rate of biodiversity loss | 2.4 | 1.6 | 1.6 | 0.8 | 0.8 |
| Fresh water use | 2.2 | 1.2 | 2.1 | 1.4 | 0.6 |
| Change in land-use | 2.7 | 0.8 | 1.6 | 0.8 | 0.7 |
| Nitrogen cycle | 2 | 1.4 | 1.6 | 1.2 | 0.3 |
| Chemical pollution | 0.7 | 0.9 | 1.9 | 4.5 | 2 |
| Geophysical risk | 1.1 | 0.7 | 1.0 | 1.8 | 3.2 |

**Table 4** Global social indicators (current global average values compared to target/limit)

| Indicators | Unit | Current | Target | Comment/source |
|---|---|---|---|---|
| Youth opportunity | | | | |
| Under 5 mortality | Deaths per 1000 live births | 51 | 17 | Millennium Development Goals (UN 2013) |
| Gender equity | | 0.66 | 1 | Millennium Development Goals (UN 2013) |
| Percentage of female in schools | % | 85 | 95 | 495.9 m illiterate women in 2007 (UN 2010a) |
| Youth unemployment rate | % | 12.4 | 12.8 | 2012 rate and 2018 estimate by UN-ILO (ILO 2013) |
| Average life expectancy | years | 70 | 70 | 70 is 2015 target/United Nations (UN 2013) |
| Economy | | | | |
| Unemployment rate | % | 6 | 6* | *Estimated (ILO 2013) |
| Gini coefficient | | 0.52 | 0.2* | *Estimated (The Conference Board of Canada 2011) |
| Percentage of population living in slums | % | 25 | 18 | Millennium Development Goals (UN(2013) |
| GDP | $/cap | 10 496 | 20 000* | b$74910, 7.13 million pop, *Estimated |
| Energy access and intensity | | | | |
| Percentage of city with authorized electrical service | % | 94 | 100 | 0.21 million urban residents w/o access (IEA 2011) |
| Percentage of city with access to clean energy for cooking | % | 88 | 100 | 0.43 million urban residents w/o access (IEA 2011) |
| Energy intensity | MJ/$ | 8.9 | 8.9 | Wikipedia: List of countries by energy intensity, 2003 |
| Mobility and connectivity | | | | |
| Number of personal automobiles per capita | vehicle/cap | 0.15 | 0.2 | 1.02 billion in 2010, 1.58 billion in 2020 |
| Daily number of public transport trips per capita | trips/cap/day | 0.35 | 0.35* | *Estimated |
| Number of internet connections | % population | 40 | 50 | Internet Live Stats (2014) |
| Percentage of commuters using a travel mode other than a personal vehicle to work | % | 30 | 50* | *Estimated |
| Transportation fatalities | per 100 000 population | 17.2 | 8.6* | World Health Organization 2013 |
| Commercial air connectivity | # of destinations | | | |
| Institutions | | | | |
| Ease of doing business—World Bank (downscaled from country to city level) | | 95 | 95 | International Finance Corporation (2014) |
| Number of convictions for corruption by city officials | Per 100 000 population | 42.7 | 50 | Index average (Transparency International 2014) |
| Tax collected as a percent of tax billed | % | | | TBD from GCI |
| Debt service ratio | | | | TBD from GCI |
| Basic services | | | | |
| Percentage of population with regular solid waste collection | % | 50 | 80* | Urban solid waste management, *Estimated |
| Percentage of city population served by wastewater collection | % | 76 | 80* | 2008, Urban regions, www.worldwaterweek.org, *Estimated |
| Percentage of population served with potable water supply | % | 81 | 95* | *Estimated (UNICEF-WHO 2012) |
| Security and public safety | | | | |
| Number of fire-related deaths | Per 100 000 population | 3.6 | 0.5* | 265 000 deaths/y/WHO 2014, *estimated |
| Number of homicides | Per 100 000 population | 6.1 | 3.05* | 437 000 Cases in 2013 (UNDOC 2014), *estimated |
| Violent crime rate | Per 100 000 population | | | TBD from GCI |

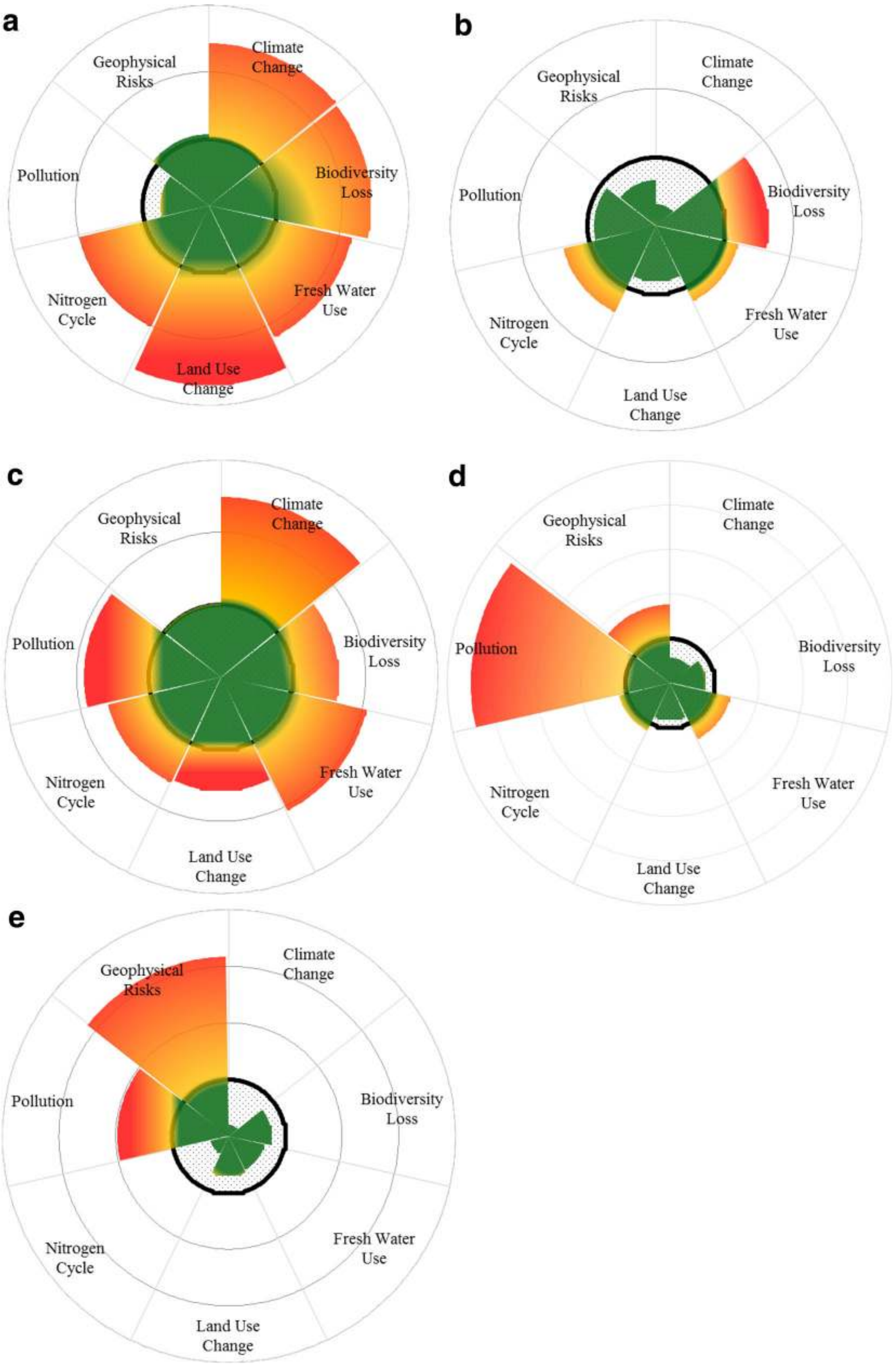

**Fig. 3** Bio-physical performance of five cities versus global average: **a** Toronto; **b** Sao Paulo; **c** Shanghai; **d** Mumbai; **e** Dakar

study by Université Catholique de Louvain and the World Health Organization (WHO) in (2012) (Guha-Sapir et al. 2013). Figure 3b compares Sao Paulo with global averages of physical science indicators.

With a population of 18.4 million (2010 data), Shanghai is China's largest metropolitan, and, like Sao Paulo, is susceptible to flooding (Kennedy et al. 2014). Greenhouse gas emissions and air quality are relatively higher than global averages (Fig. 4c). The levels of $CO_2$ equivalent emissions and particulate matter (PM2.5) are reported as 11.7 $tCO_2e$/cap/year and 81 μg/$m^3$, respectively. The average domestic fresh water use in Shanghai Metropolitan Area is 411 L/cap/day, which is four times the global 'Water Right'-level proposed by the United Nations.

Mumbai is India's largest metro area: Air quality is as poor as Shanghai's. Mumbai also has disproportionately high impacts on biodiversity loss, fresh water use, and land-use change (Fig. 4d).

Dakar Metropolitan Area covers 1 % of Senegal's land area; however, it is home to nearly 50 % of the country's urban population. Much of the city's population reside in the 'Pre-Urban' part of the metropolitan, and is vulnerable to natural disasters, especially flooding and coastal erosion, which is exacerbated by weak local governance and rising sea levels (Wang et al. 2009).

The city is the economic and political hub of the country, and any impact to Dakar affects Senegal overall. For example, more than 5 % of Dakar Metropolitan Area is exposed to high-risk natural hazards. The city's population has grown an average 1 % per year since 1988; current predictions estimate the city reaching 8.5 million by 2050 (Hoornweg and Pope 2013). The city also suffers from high ambient air pollution with 80 μg/$m^3$, compared to the WHO targets of 10 μg/$m^3$. Access to clean water is not provided to 3 % of the population, and nearly 25 % of the population receives no formal solid waste collection (Fig. 3e).

### Socio-economic indicators

The socio-economic limits for the five major cities are compared to the global average with a scale of 1 (Table 5). Compared to the global average, only Shanghai has a better level of youth opportunity; Toronto's youth unemployment is highest of the five pilot cities, yet it has the lowest Gini coefficient. Dakar's economic challenges are manifest, reflected by relatively low youth opportunity and low economic performance (Table 5, and Appendix S2).

Toronto has the highest gross domestic product (GDP) per capita among all five pilot cities ($51,000), and Dakar the lowest at $3,700. Nearly 20 % of Shanghai's residents do not have access to solid waste and wastewater collection, while this number is more than 60 % for the people who live in Mumbai Metropolitan Region. Mumbai also has the second highest fire-related deaths among the five pilot cities, after Dakar.

On average, compared to the global values, Toronto has a larger per capita economy, full energy access, and higher public safety and security indicators (Fig. 4a). Sao Paulo, on the other hand, has lower youth opportunity and per capita economy; although the city has relatively high service levels in areas such as mobility and connectivity, and basic services (Fig. 4b).

Shanghai is well served by its public transportation system and provides relatively high level socio-economic boundaries (Fig. 4c). Compared to Toronto, Shanghai's higher Gini coefficient and lower per capita income are key economy indicators.

Comparing Toronto, Shanghai, and Sao Paulo with Mumbai and Dakar, the significant need for improved economy, youth opportunity, and mobility and connectivity is evident. Mumbai also lags in providing basic services such as waste collection and improved sanitation (Fig. 4d, e).

## CONCLUSIONS AND FUTURE DIRECTIONS

Residents of cities drive the world's material and energy flows—and their associated global environmental impacts; while cities are also particularly vulnerable to impacts associated with unsustainable development of human societies. Much urban infrastructure is fragile, e.g., roads, railways, buildings, and water supply, and vulnerable to flooding and landslides. Cities are also immobile: they cannot get out of harm's way. Many are coastal, threatened by increasing sea levels and storm intensities associated with climate change.

The challenges and integrated nature of sustainable development and associated threats to planetary boundaries are well developed through Rockstrom et al. (2009) and Steffen et al. (2015). The bio-physical limits capture well the requirements and magnitude of global impacts. This work is augmented by Dearing's socio-economic boundaries outlining a 'safe and just space for humanity' (Dearing et al. 2014) and the sustainable development goals (SDGs 2015).

This paper provides a methodology that enables cities to be more active players (with clear metrics of progress) in the monitoring, and hopefully positive shift away from unsafe progress against planetary boundaries. The city level is considered a critical unit for sustained action. The methodology facilitates integration across boundaries and targets, as well as integrating local and global impacts. Each city can develop its target to sustainability. Selected data inputs are readily available and most can be third-party verified, providing a means to more effectively target finance for sustainable-city actions. Efforts can be readily monitored and compared across cities.

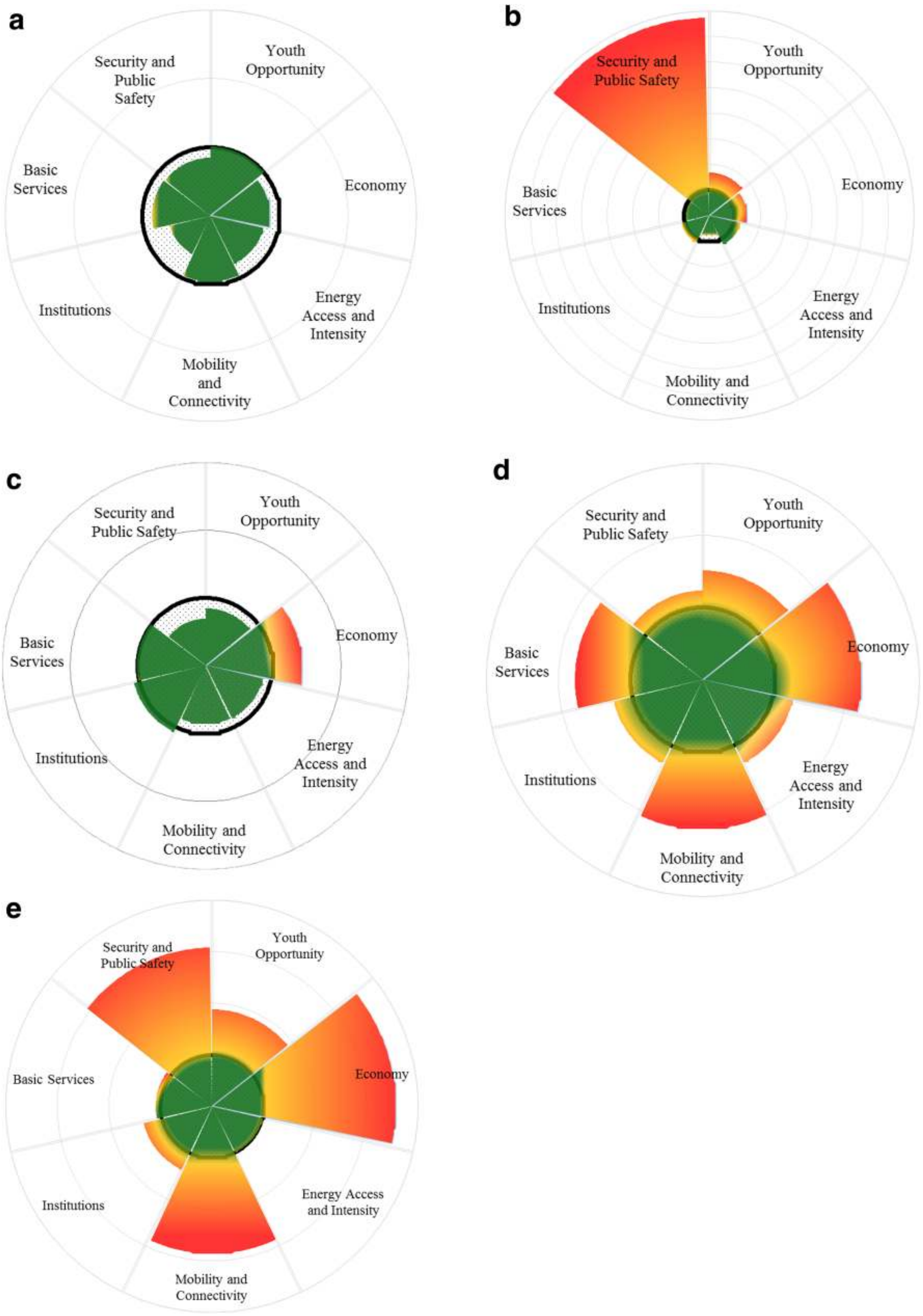

**Fig. 4** Socio-economic performance of five cities versus the global average: **a** Toronto; **b** Sao Paulo; **c** Shanghai; **d** Mumbai; **e** Dakar

**Table 5** Status of five major world cities' socio-economic indicators compared to a global scale of 1

| Indicators | Toronto | Sao Paulo | Shanghai | Mumbai | Dakar |
|---|---|---|---|---|---|
| Youth opportunity | 1.0 | 1.7 | 0.8 | 1.5 | 1.9 |
| Economy | 0.9 | 1.5 | 1.4 | 2.2 | 3.6 |
| Energy access and Intensity | 0.8 | 1.2 | 0.8 | 1.2 | 1.0 |
| Mobility and connectivity | 1.0 | 0.8 | 0.9 | 2.1 | 2.9 |
| Institutions | 0.6 | 1.1 | 1.1 | 1.3 | 1.4 |
| Basic services | 0.9 | 0.9 | 1.0 | 1.8 | 1.1 |
| Security and public safety | 0.8 | 7.7 | 0.7 | 1.2 | 3.1 |

Looking to the future, the proposed methodology and city targets if used by the majority of the world's larger cities could potentially support an 'international agreement on sustainable development' facilitated through cities. The methodology also facilitates comparisons between cities. For example, Toronto and Shanghai's required contribution to climate change is seven times greater than Dakar or Sao Paulo. Similar trends are observed with rates of biodiversity loss and change in land-use.

Data associated with these evaluated cities are expected to be regularly updated. A global effort is needed to collect this information, although as we show through these five pilot cities, the methodology is both sufficiently simple and comprehensive enough to enable application and analysis across all urban regions with populations over 5 million.

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## REFERENCES

Ahern, J. 2013. Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology* 28: 1203–1212.

Banister, D. 2012. Assessing the reality—transport and land use planning to achieve sustainability. *The Journal of Transport and Land Use* 5: 1–14.

Bechtel, M.M., and K.F. Scheve. 2013. Mass support for global climate agreements depends on institutional design. *Proceedings of the National Academy of Sciences* 110: 13763–13768.

Bettencourt, L., and G. West. 2010. A unified theory of urban living. *Nature* 467: 912–913.

Blackburn, S., and M. Pelling. 2014. Coastal megacities: Risks and opportunities. *Global Change* 82: 8–11.

Committee on Climate Change (CCC). 2014. Setting a target for emission reduction. Retrieved August 7, 2014, from http://www.theccc.org.uk/tackling-climate-change/the-science-of-climate-change/setting-a-target-for-emission-reduction/.

Dahl, A.L. 2012. Achievements and gaps in indicators for sustainability. *Ecological Indicators* 17: 14–19.

Dearing, J.A., R. Wang, K. Zhang, J.G. Dyke, H. Haberl, M.S. Hossain, P.G. Langdon, T.M. Lenton, et al. 2014. Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change* 28: 227–238.

de Brito Jr., I., B.C. Kawasaki, A. Leiras, and H.T.Y. Yoshizaki. 2011. The profile of the population affected by natural disasters in Brazil. POMS 23rd Annual Conference, Report 025-1388.

Demographia 2006. World urban population density by country & area. Retrieved August, 28, 2014, from http://www.demographia.com/db-intlua-area2000.htm.

Duren, R.M., and C.E. Miller. 2012. Measuring the carbon emissions of megacities. *Nature Climate Change* 2: 560–562.

Gerst, M., P. Raskin, and J. Rockström. 2013. Contours of a resilient global future. *Sustainability* 6: 123–135.

Gnanapragasam, N.V., B.V. Reddy, and M.A. Rosen. 2010. A methodology for assessing the sustainability of hydrogen production from solid fuels. *Sustainability* 2: 1472–1491.

Grimm, N., S. Faeth, N. Golubiewski, C. Redman, J. Wu, X. Bai, and J. Briggs. 2008. Global change and the ecology of cities. *Science* 318: 756–760.

Guha-Sapir, D., and P. Hoyois. 2013. Disaster deaths: Proposed indicators for monitoring disaster-related mortality. In *Disaster risk management in post-2015 development goals: Potential targets and indicators*

Guha-Sapir, D., P. Hoyois, and R. Below. 2013. Annual disaster statistical review 2012: The numbers and trends. Centre for Research on the Epidemiology of Disasters (CRED).

Hoornweg, D., L. Sugar, and L.T. Gomez. 2011. Cities and greenhouse gas emissions: Moving forward. *Environment & Urbanization* 23(1): 207–228.

Hoornweg, D., and M. Freire. 2013. Building sustainability in an urbanizing world. The World Bank Urban Development Series Knowledge Papers, No. 17, Washington, USA.

Hoornweg, D., and K. Pope. 2013. Socioeconomic pathways and regional distribution of the world's 101 largest cities. Global Cities Institute Working Paper No. 04.

International Energy Agency (IEA). 2011. World energy outlook—energy for all. Organisation for Economic Co-operation and Development (OECD)/IEA, Paris, France.

International Finance Corporation (IFC). 2014. Economy rankings. Retrieved August, 14, 2014, from http://www.doingbusiness.org/rankings.

International Labour Organization (ILO). 2013. Global youth unemployment trends and projections from 2007 to 2013. Retrieved August, 14, 2014, from http://www.ilo.org/global/about-the-ilo/multimedia/maps-and-charts/WCMS_212430/lang–en/index.htm.

International Standardazation Organization (ISO). 2014. *Sustainable development in communities: City indicators for service delivery and quality of life*. ISO, Report 37120, Geneva, Switzerland.

International Union for Conservation of Nature (IUCN). 2014. The IUCN red list of threatened species. Retrieved August, 19, 2014, from http://www.iucnredlist.org/about/summary-statistics#Tables_1_2.

Internet Live Stats. 2014. Internet users. Retrieved August, 14, 2014, from http://www.internetlivestats.com/internet-users/.

Kennedy, C.A., A. Ramaswami, S. Carney, and S. Dhakal. 2011. Greenhouse gas emissions baseline for global cities and metropolitan regions. In *Cities and climate change: Responding to an Urent Agenda*.

Kennedy, C.A., N. Ibrahim, I. Stewart, A. Fachini, and R. Mele. 2014. *An urban metabolism survey design for megacities*. Toronto: University of Toronto and Enel Foundation.

MSW Management. 2014. Municipality waste management. Retrieved August, 14, 2014, from http://www.mswmanagement.com/MSW/MSWhome.aspx.

Newman, P., and I. Jennings. 2008. *Cities as sustainable ecosystems: Principles and practices*. Washington: Island Press.

Nordhaus, T., M. Shellenberger, and L. Blomqvist. 2012. *The planetary boundaries hypothesis: A review of the evidence*. Oakland: Breakthrough Institute.

Raworth, K. 2012. *A safe and just space for humanity*. Oxford: Oxfam International.

Rockstrom, J., W. Steffen, K. Noone, A. Persson, F.S. Chapin, E.F. Lambin, T.M. Lenton, M. Scheffer, et al. 2009. A safe operating space for humanity. *Nature* 461: 472–475.

Rosen, M.A. 2012. Engineering sustainability: A technical approach to sustainability. *Sustainability* 4: 2270–2292.

Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 327: 6223.

Sustainable Development Knowledge Platform. 2014. Sustainable development goals. Retrieved August, 29, 2014, from http://sustainabledevelopment.un.org/?menu=1300.

Transparency International. 2014. Corruption perceptions index 2013.

UNICEF and World Health Organization (WHO). 2012. Progress on drinking water and sanitation 2012 update. UNICEF-WHO, New York, USA.

United Nations. 2010. The World's Women 2010: Trends and statistics. United Nations, New York, USA.

United Nations. 2013. The millennium development goals report. United Nations, Report 13-26318, New York, USA.

United Nations. 2014. World urbanization prospects. Department of Economic and Social Affairs.

United Nations. 2015. Sustainable development goals.

United Nations Office on Drugs and Crime (UNDOC). 2014. *Global study on homicide 2013: Trends, contexts, data*. United Nations Office on Drugs and Crime, Vienna, Austria

Valipour, M., M. Ahmadi, M. Raeini-Sarjaz, M. Sefidkouhi, A. Shahnazari, R. Fazlola, and A. Darzi- Naftchali. 2015. Agricultural water management in the world during past half century. *Archives of Agronomy and Soil Science* 61(5): 657–678.

Wang, H.G., M. Montoliu-Munoz, and N.F.D. Gueye. 2009. *Preparing to manage natural hazards and climate change risks in Dakar, Senegal: A spatial and institutional approach*. The World Bank.

World Bank. 2000. Senegal urban mobility improvement project. Report 20345-SE.

World Bank. 2010. World development report: Development and climate change.

World Bank. 2011. World development report: Gender equality and development.

World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD). 2011a. Corporate value chain (scope 3) accounting and reporting standard. WRI and WBCSD, Conches-Geneva, Switzerland

World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD). 2011b. Greenhouse gas protocol product standard adopted by the sustainability consortium. WRI and WBCSD, Conches-Geneva, Switzerland

World Wildlife Fund (WWF). 2014. Living planet report 2014. WWF, Gland, Switzerland

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