Greenhouse Gas Emissions from Global Cities Under SSP/RCP Scenarios, 1990 to 2100

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Abstract

Projections of greenhouse gas (GHG) emissions are critical to better understanding and anticipating future climate change under different socio-economic conditions and mitigation strategies. The climate projections and scenarios assessed by the Intergovernmental Panel on Climate Change, following the Shared Socioeconomic Pathway (SSP)-Representative Concentration Pathway (RCP) framework, have provided a rich understanding of the constraints and opportunities for policy action. However, the current emissions scenarios lack an explicit treatment of urban emissions within the global context. Given the pace and scale of urbanization, with global urban populations expected to increase from about 4.4 billion today to about 7 billion by 2050, there is an urgent need to fill this knowledge gap. Here, we estimate the share of global GHG emissions emanating from urban areas from 1990 to 2100 based on the SSP-RCP framework. The urban GHG emissions are presented in five regional aggregates and are based on a combination of the urban population share, 2015 urban per capita CO_2eq emissions, SSP-based national CO_2eq emissions, and recent analysis of urban per capita CO_2eq trends. We find that urban areas account for the majority of global GHG emissions in 2015 (61.8%). Moreover, the urban share of global GHG emissions progressively increases into the future, exceeding 80% in some scenarios by the end of the century. The combined urban areas in Asia and Developing Pacific, and Developed Countries account for 65.0% to 73.3% of cumulative urban emissions between 2020 and 2100 across the scenarios. Given these dominant roles, we describe the implications to potential urban mitigation in each of the scenario narratives in order to meet the goal of climate neutrality within this century.

Keywords: urban emissions, climate change, emission scenarios, emissions mitigation, greenhouse gases, climate neutrality

1. Introduction

Scenarios of future greenhouse gas (GHG) emissions remain a critical element in climate change research and policymaking, providing a means to better understand the relationship between key drivers of socio-economic activity, atmospheric concentration targets, and integrated emission outcomes. For the last decade researchers have developed the Shared Socioeconomic Pathway (SSP)-Representative Concentration Pathway (RCP) framework (O'Neill et al., 2020) as assessed by the Intergovernmental Panel on Climate Change (IPCC). The framework provides a common approach that combines pathways for radiative forcing (RCPs) and five SSPs that represent varying projections of societal factors such as demographics, development, governance, and technological change (van Vuuren et al., 2014). Shared Policy Assumptions (SPAs) were further incorporated into the working scenario framework to offer additional insight and outcomes associated with policy actions (van Vuuren et al., 2014; Kriegler et al. 2014; O'Neill et al., 2020). The SPAs range from early to late accession for developing countries as well as delayed transitions to global cooperation (Riahi et al., 2017; Kriegler et al., 2014). When incorporated into a suite of Integrated Assessment Models (IAMs), the scenarios provide depictions of the future reflecting the combination of underlying socio-economic conditions, physical targets and policy action (van Vuuren et al., 2017a). We refer to the particular combination of SSP, RCP, and SPA values used here as the "SSP-RCP-SPA framework."

The degree of urbanization is a key factor within the SSPs owing in part to the large share of global emissions that emanate from, or are indirectly driven by, urban activities globally. For example, work by Moran et al., (2018) found that 68% of the global carbon footprint (CF, also sometimes referred to as Scope 3 or consumption-based emissions) was driven by urban areas in 2015. Moreover, the top 100 emitting cities worldwide account for about 18% of the global carbon footprint. Regional estimates have found similarly large proportions. In China, Wiedenhofer et al. (2017) found that urban households drive 75% of the national CF in 2012, a share similar to that of Feng and Hubacek (2016). In the U.S., Jones and Kammen (2014) estimated that the CF of urban areas ("metropolitan statistical areas") accounted for 80% of the national CF in the year 2007. In the US, Gurney et al., (2020) found that the urban emissions share ranged from 45% to 87% depending upon the definition of emissions scope and urban boundary.

In addition to the climate implications, urbanization has wide-ranging consequences for the Sustainable Development Goals (SDGs) and the opportunities in urban areas can either accelerate or hinder sustainability transitions (Seto et al., 2017). Urban planning decisions simultaneously determine the level of access to basic services and housing (Brelsford et al., 2017) as well as the ability of urban areas to provide greater social welfare while lowering emissions and improving environmental quality (Kılkış, 2019). The consumption-based emissions impact of urban areas are also not confined to local emissions and reach across the globe (Harris et al., 2020). Collaboration across a global system of urban areas is vital for safeguarding planetary resources (Seitzinger et al., 2012) while enabling effective climate mitigation pathways.

There has been growing recognition of the importance of cities for climate change mitigation over the past decade (Gurney et al., 2015; Hsu et al., 2015). For example, the first standalone chapter on urban mitigation of climate change was published in the IPCC Fifth Assessment Report (Seto et al., 2014). Cities were further highlighted during the 43rd Session of the IPCC in 2016, when the plenary voted for a Special Report on Climate Change and Cities in the IPCC 7th Assessment Cycle and co-organized the first Cities and Climate Change Science Conference. Moreover, the Special Report on Global Warming of 1.5°C identified urban and infrastructure systems as one of the four systems needing to undergo transformative systemic change if the world is to limit global warming (de Coninck et al., 2018). Yet, despite this growing recognition, there is a significant gap in knowledge about the urban share of global GHG emissions, especially in the coming decades.

Within the SSP-RCP-SPA framework, urbanization was singularly accounted for by defining the share of national population residing in urban areas in each of the five SSPs (Jiang and O'Neill, 2017). The degree of urbanization that is reached differs widely across the SSPs (Jiang and O'Neill, 2017). Urbanization is also incorporated indirectly via its effect on consumption patterns, income growth, as well as the efficiency with which energy is being used (Jiang and O'Neill, 2017). For example, the urban population share will indirectly influence scenario elements such as urban-versus-rural population, the rate of technological development, the direction of technological progress (e.g., environmental or efficiency and productivity oriented), and other societal factors based on lifestyles and policies, urban planning, and energy and environmental policies (O'Neill et al., 2014).

Other than the urban population share within the SSP-RCP-SPA framework, explicit representation of urban emissions has been limited in the literature. For example, recent work used various datasets to estimate urban energy use in 2050 (Creutzig et al., 2015) and savings in direct final energy use considering systemic infrastructural and behavioral changes for low-carbon development (Creutzig et al., 2016b). Annual and cumulative urban energy use for heating and cooling based on operational energy were also projected out to 2050. Other studies estimated emission reductions from existing as well as new urban infrastructure (Creutzig et al., 2016a). Finally, scenarios were considered for urban density and building retrofit options for energy efficiency (Güneralp et al., 2017).

None of these studies, however, have explicitly quantified a complete urban emissions trajectory within the global context - within the SSP-RCP-SPA framework or otherwise. This lack of explicit treatment of urban areas within the emissions scenario research makes it difficult to understand the key dynamics in the evolving contribution of urban areas to global GHG emissions, particularly given the growing urban share of global population and GDP. This hampers an understanding of the limits and opportunities for mitigation and adaptation in this crucial portion of global emissions.

This work aims to address this gap in representing urban emissions within the projected global context by using recent related research on urban emissions combined with the existing underlying dynamics of the SSP-RCP-SPA framework to quantify urban GHG emissions regionally and globally out to 2100. We do not explicitly incorporate urban mitigation or adaptation in the scenario outcomes but discuss the implications of urban policy for the projected results.

Hence, the practical outcomes reported here quantify the urban emissions share by geographic/developmental region within the total emissions at a global scale in a way that is consistent with the scenarios in the scenario matrix architecture. We further use the results to discuss the potential for including regional urban-specific strategies that can further alter future GHG emissions. This paper outlines the methods used to quantify urban GHG emissions within the SSP-RCP-SPA framework, presents the results, and discusses these outcomes in the context of urban climate change policy.

2. Methods

In its simplest form, the method employed here to estimate the urban component of consumption-based GHG emissions within each of the SSP-RCP-SPA scenarios combines three data elements: 1) estimates of the 2015 urban per capita GHG emissions; 2) a time series that characterizes changes in the urban per capita GHG emissions into the future; and 3) a time series of urban population. This can be expressed in general as,

$$E(c,y,s) = e_{2015}(c) * \delta(y,s,r) * P(c,y,s) \qquad (1)$$

where the urban per capita GHG emissions, E, for a specific country, c, a specific year, y, and a specific SSP-RCP-SPA scenario, s, is equal to the per capita urban emissions in 2015, e_{2015}, multiplied by a temporal adjustment, δ, specific to year, scenario, and global region or country, r, multiplied by urban population, P.

The changes in urban per capita emissions and urban population, in turn, are derived from a series of additional datasets. Among these are national emissions data (aggregated from the downscaled and spatially-explicit SSP projections of CMIP6 by Gidden et al., (2019)), recent analysis of urban emission trends, estimates of national population, and the urban population share by country. Hence, input data to the urban GHG estimation procedure includes seven publicly available datasets (Figure 1, Table 1).

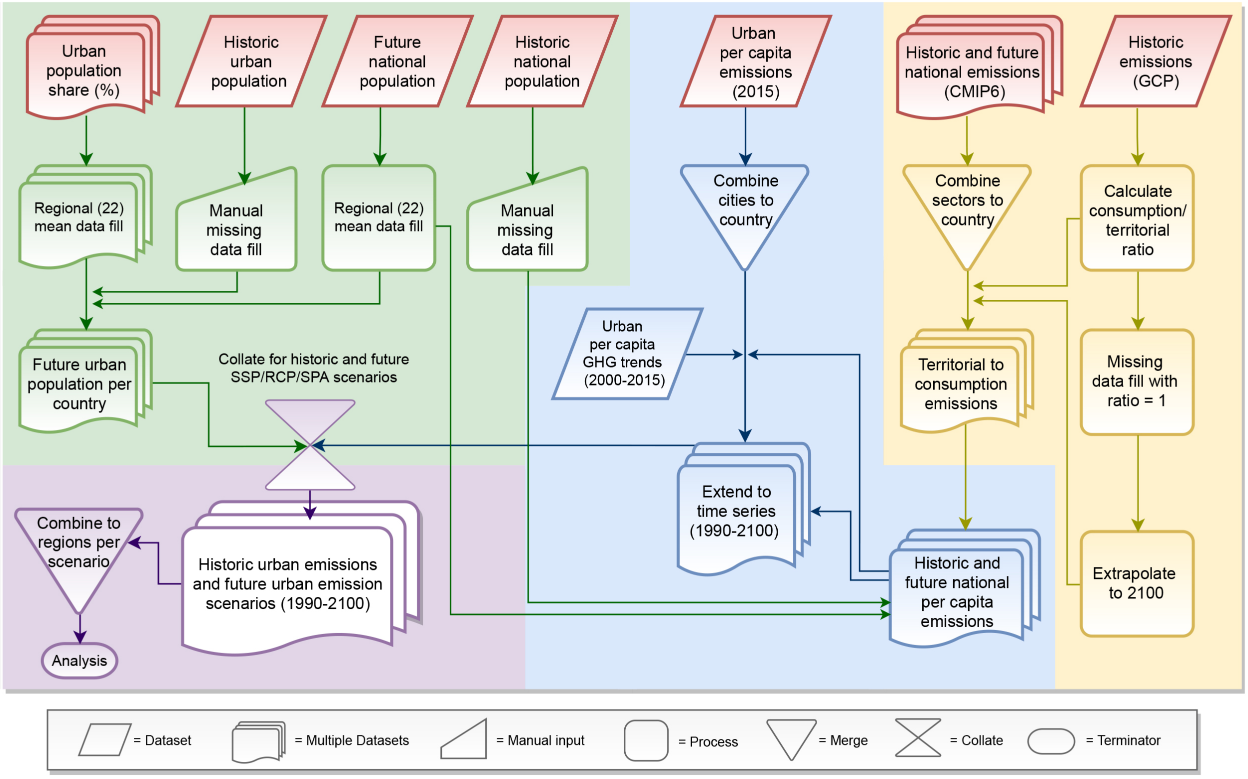

Figure 1. *Schematic representation of the numerical method to estimate global urban GHG emissions, 1990 to 2100. Red flowchart symbols denote input datasets (see Table 1). Green shaded areas denote population data and processing; blue shading denotes per capita emissions data and processing; yellow shading denotes emissions data and processing; purple shading denotes the final outcome.*

2.1. Historic and future urban population

The share of national population projected to reside in urban areas is critical to estimating the total urban population by country. The urban population share data starts in 2010 and is projected to 2100 as rapid, moderate, mixed, and slow urbanization rates in five-year increments, for each of the five SSPs (Jiang and O'Neill, 2017). The years 2010 and 2015 are replaced by observed urban share data (described below). A total of 55 small island nations and territories were missing from the urban population share dataset and were filled using regional values constructed from the population-weighted mean percentage urban share in each of 20 global regions. The regional aggregate definitions used here and in other points within the estimation procedure include a 5-, 10-, and 20-region aggregate grouping of countries (see supplementary information for further details). The final results for urban GHG emissions reported in this study are for the 5-region grouping.

Table 1. *Input data used to estimate global urban GHG emissions with core characteristics and data sources.*

Input data	**Timespan**	**Key attribute**	**Missing data filling** (see supplementary Information)	**Reference**
Urban population share	2010-2100 (5-year increments)	5 SSP projections	55 small island nations and territories were missing, filled with population-weighted mean regional aggregates.	(Jiang and O'Neill, 2017)
Historic national population	1950-2020 (annual)		14 small island nations and territories were missing, filled with data from online resources.	(UN DESA, 2019a)
Future national population	2010-2100 (5-year increments)	5 SSP projections	55 small island nations and territories were missing, 2015 & 2020 filled with historic data. Constant at 2020 value for 2020-2100.	(KC and Lutz, 2017)
Historic national CO_2 emissions	1959-2019 (territorial); 1990-2018 (consumption)	Consumption and territorial CO_2 emissions	32 countries were missing from territorial, 130 missing from consumption. Used for national-scale ratio of consumption-to-territorial emissions. Ratios filled as "1" in most missing cases and a regional aggregate mean in remaining.	(GCP, 2020) (Friedlingstein et al., 2020), updated from (Peters et al., 2011)
Historic urban population	1950-2019 (annual increments)	By nation	16 small island nations and territories were missing, filled with data from online resources.	(UN DESA, 2019b)
Urban per capita CO_2eq emissions sample	2015	13,063 cities	Aggregated to national via population-weighted mean.	(Moran et al., 2018)
Historic and future national GHG (CO_2, CH_4) emissions	1990-2100	By country past and future (7 SSP-RCP-SPA combinations)	28 small island nations, territories and countries missing. No filling performed	(Gidden et al., 2019), (IIASA, 2019)

Historic national population is retrieved from the United Nations World Population Prospects data archive, providing population from 1950 to 2020 (UN DESA, 2019a). A total of 14 small island territories were missing and manually added using estimates from online resources. Similarly, historic urban population (within nations) from 1950 to 2019 is retrieved from United Nations statistics (UN DESA, 2019b). A total of 16 small island territories were manually added using estimates from online resources (see supplementary information for further details).

The future national population is retrieved from the SSP web-database hosted at IIASA (IIASA, 2018; KC and Lutz, 2017). These contain national population projections according to the five SSP scenarios, spanning the 2015 to 2100 time period (five-year increments). A total of 55 small island nations and territories were missing. The year 2015 and 2020 of the missing data were filled with the 2015 and 2020 values from the national historic population data and maintained at the 2020 value to the year 2100 (see supplementary information). The 55 small island nations and territories only account for 0.5% of 2020 global population and hence, have little impact on the results presented here.

The combination of the urban population shares and the future population allows for an estimation of the future urban population according to the five SSP scenarios or *P*, in equation 1.

2.2. Emissions data, conversion and trends

Two datasets supplying GHG emissions were used. The first, from the Global Carbon Project (GCP), provided estimates of national historic anthropogenic carbon dioxide (CO_2) emissions (no CH_4, no biogenics) from 1959 to 2019 for territorial emissions (emissions directly emanating from a geographic location - often referred to as "Scope 1" or "direct" emissions) and 1990 to 2018 for consumption-based emissions (often referred to as "Scope 3" emissions) (GCP, 2020; Friedlingstein et al., 2020 updated from Peters et al., 2011).

The GCP data were used to construct a historic (1990 to 2018) national-scale ratio of consumption-to-territorial emissions. These historic ratio values were extrapolated to 2100 using linear regression of the national ratio trend over the 1990 to 2018 time period. To ensure that the global total consumption-based emissions maintained consistency with the territorial emissions, the consumption-based emissions were scaled by the ratio of the global territorial-to-consumption emissions value (see supplementary information for further details).

The second data set used for GHG emissions was the harmonized and downscaled data produced for the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Feng et al., 2020). This national-scale territorial GHG emissions dataset ensures consistency among historical emissions (Hoesly et al., 2018) and future emission trajectories with 2015 as the transition year (Gidden et al., 2019; IIASA, 2019). The emissions time series represent national emissions historically and for the future (1990 to 2100) according to seven SSP-RCP-SPA variants. The low near-term climate forcing, and the overshoot scenarios are not included in the present study. The simulations were produced by the five different IAMs described in Table 2. The emissions include numerous sector categories and multiple gases. For the purposes here, the national emissions were summed across all CO_2 and CH_4 emission categories except those for aviation and marine bunker fuels and biogenic (e.g. land use, grassland, and peat burning) sources. Nitrous oxide (N_2O) is not quantified at the country scale in the dataset and hence, not considered here (Gidden et al., 2019). A 100-year global warming potential (GWP) value of 25 was used for CH_4 (Gütschow et al., 2016) to maintain consistency with the data sources used to generate the urban per capita GHG estimate though recent guidance from the IPCC recommends a value of 34.75. These emissions are transformed to represent national consumption emissions via the national-scale ratio of consumption-to-territorial emissions, estimated from the GCP results. A total of 220 countries were present.

Table 2. *Summary of the marker models and scenario matrix architecture and urbanization inputs*

Model / Reference	**Scenario Framework Description**			**Input**
	SSP	**RCP /Radiative Forcing Level**	**SPA** (Kriegler et al., 2014)	**Urbanization Rate** (Jiang and O'Neill, 2017)
IMAGE (Rogelj et al., 2018)	SSP1 (Green-growth, Sustainability)	1.9 W/m^2 (Highest stringency)	SPA1 (Cooperative world, broad and rapid participation)	Rapid
IMAGE for IMAGE (van Vuuren et al., 2017b)	SSP1 (Green-growth, Sustainability)	2.6 W/m^2 (High stringency)	SPA1 (Cooperative world, broad and rapid participation)	Rapid
GCAM4 (Calvin et al., 2017)	SSP4 (Inequality)	3.4 W/m^2 (Intermediate stringency)	SPA4 (Partial participation/ regional differentiation)	Moderate (high-income) or Rapid (middle and low-income countries)

MESSAGE-GLOBIOM (Fricko et al., 2017)	SSP2 (Middle of the Road)	4.5 W/m^2 (Less stringency)	SPA2 (Geographically fragmented with delayed convergence)	Moderate
GCAM4 (Calvin et al., 2017)	SSP4 (Inequality)	6.0 W/m^2	SPA4 (Partial participation/ regional differentiation)	Moderate (high-income) or Rapid (middle and low-income countries)
AIM/CGE (Fujimori et al., 2017)	SSP3 (Regional Rivalry)	7.0 W/m^2	SPA0 (Exogenous emissions pathway/ baseline)†	Slow
REMIND-MAgPIE (Kriegler et al., 2017)	SSP5 (Fossil-Fuel Development)	8.5 W/m^2	Baseline	Rapid

†AIM/CGE SSP3-7.0-SPA0 is matched with SPA0 rather than SPA3.

Historic and future national per capita GHG emissions were calculated as the ratio of the national GHG emissions (1990-2100) divided by the national population for each scenario in Table 2. Missing values (due to 28 missing national emission entries) are filled using the 20-region mean national per capita CO_2eq emissions (see supplementary information for further details).

Finally, the non-zero urban per capita GHG (CO_2, CH_4, N_2O) emissions were retrieved for 13,063 individual cities and these reflect the individual per capita urban CF for the year 2015 (Moran et al., 2018). A weighted mean (by population) is used to aggregate these values into national representative values for 2015 (e_{2015} in equation 1). The urban per capita CO_2eq values were extended into a time series using additional datasets (representing δ in equation 1). For the time period from 1990 to 2000, the trends of national per capita GHGs were used. For the 2000 to 2014 and 2016 to 2020 time periods, we use the urban per capita CO_2 trend values as developed in (Luqman et al., 2021) in which all countries within each of the 10-region aggregates were operated on by the same trend value (see supplementary information for trend values). For 2020 to 2100, urban per capita CO_2eq emissions were adjusted following the increments in national per capita CO_2eq emissions under the seven SSP-RCP-SPA scenarios.

The national-scale urban per capita consumption CO_2eq emissions, according to the seven SSP-RCP-SPA scenarios, are combined with the five national-scale SSP urban population projections to achieve the urban consumption CO_2eq emissions at the national scale. These national-scale values are then summed into global regions according to the 5-region aggregate definitions.

To account for numerical instability in two of the scenarios that transition from positive to negative emissions (e.g. carbon capture or biotic strategies) in the future (IMAGE SSP1 1.9 SPA1 and IMAGE SSP1 2.6 SPA1), small adjustments were made such that the urban emissions did not exceed the global value at those singular junctures.

The analyses conducted here based on the results include comparisons across scenarios and regions on an annual urban emissions basis. In addition, the implications of the urban emission scenarios results are discussed along with the annually accumulated urban emissions.

3. Results

The outcome of these calculations provides explicit consumption-based urban CO_2eq emissions by region from 1990 to 2100 under each of the seven scenarios outlined in Table 2. Because the historical time period is constructed somewhat differently from the future time period, we provide separate presentation and discussion of each.

3.1. Regional urban emissions, 2000 to 2015

An examination of the observationally based results for the 2000 to 2015 time period offer insights into existing trends and dynamics (Figure 2). The most significant change in emission metrics occurred between the Asia and Developing Pacific and the Developed Countries regions. Urban population, urban CO_2eq emissions and national CO_2eq emissions increased between 2000 and 2015 as a share of the global total in the Asia and Developing Pacific region while the same metrics declined for the Developed Countries region. All regions witnessed an increase in the urban share of CO_2eq emissions. Urban per capita CO_2eq and national per capita CO_2eq also increased in all regions except for the Developed Countries region, for which urban per capita CO_2eq value declined slightly. All regions showed convergence of the urban and national per capita CO_2eq, with the exception of Africa and Middle East region that showed a very small divergence of per capita CO_2eq between 2000 and 2015. These dynamics are not surprising as the urban share of national emissions increases over the time period.

Across all regions and both years, except for the Asia and Developing Pacific region, the urban per capita CO_2eq value is smaller than the national CO_2eq value. In Africa and Middle East, the urban per capita CO_2eq value is slightly higher in 2000 and 2015. The regions in which urban per capita values remain smaller than national per capita values confirm the emission efficiency of urban residents as suggested in other studies (e.g. Wang et al., 2017; Ou et al., 2013).

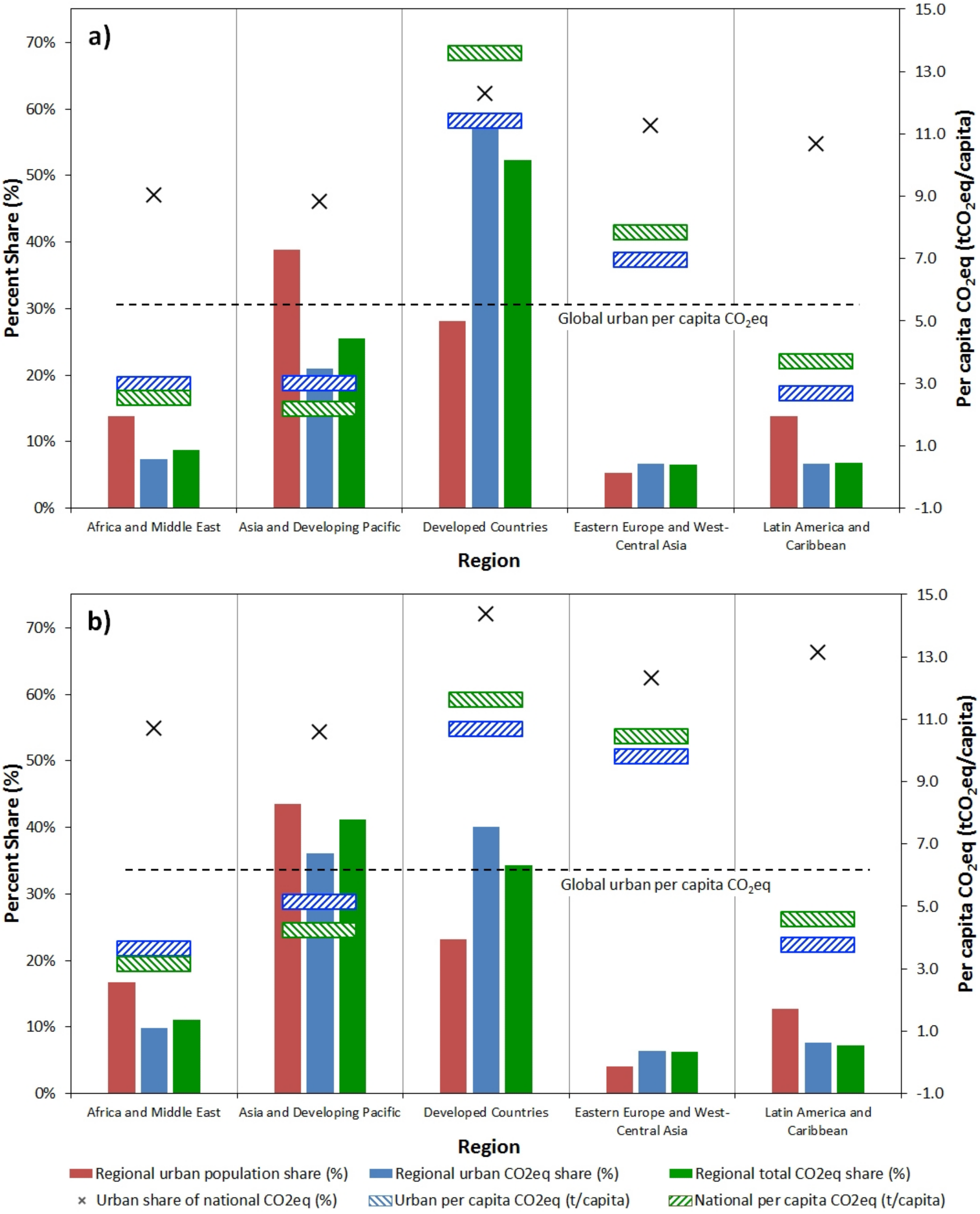

Figure 2. *Changes in six metrics associated with urban and national-scale emissions for the 5-region aggregation. a) 2000; b) 2015. The dataset is provided in the supplementary information.*

The global urban share in 2015 is 61.8%, a value somewhat lower than the mean result of the IPCC AR5 report and some literature estimates (Marcotullio et al., 2013; Seto et al., 2014). This is primarily due to the fact that the consumption emissions in this study represent the combination of CO_2 and CH_4 as opposed to just considering CO_2 emissions. Anthropogenic CH_4 emissions are often dominated by sources outside urban areas, such as gas well leakage locations. The Moran et al. (2018) study, upon which the 2015 urban per capita CO_2eq values are based in this study, estimated the global urban share in 2015 as 68%, higher than the share found here, though both studies use the same CO_2eq basis. This is likely due to differences in the aggregation of the individual urban per capita values.

3.2. Drivers of urban emissions, 1990 to 2100

Figure 3 compares the urban CO_2eq emissions and their two key drivers (urban population and urban per capita CO_2eq) for the SSP-RCP-SPA scenarios aggregated to the globe and normalized to 1990 values (i.e. ratio of given year emissions to 1990 emissions). Figure 3a, based on SSP1, represents the scenario in which divergence of urban emissions from increases in urban population takes place most rapidly, with a peak in global urban CO_2eq emissions in 2020 and sharp declines thereafter achieving neutrality (and then negative emissions) around 2065. This is driven by the decline in urban per capita CO_2eq, which is moderated by a rising urban population reaching a maximum value in 2070. The same SSP but with a larger RCP value (2.6 W/m^2 versus 1.9 W/m^2) shows the same urban population profile but a delayed decline in the urban per capita CO_2eq emissions (Figure 3b), achieving neutral (and then negative) urban emissions near 2080.

Figure 3c and 3e show the SSP4 results with two different RCP values of 3.4 W/m^2 and 6.0 W/m^2, both simulated by the GCAM model. The more dramatic decline in urban per capita CO_2eq emissions, necessitated by the lower RCP goal, results in neutral urban CO_2eq emissions (and negative thereafter) around 2080. In the case of the higher RCP 6.0 scenario, the urban per capita CO_2eq values show a much more gradual decline resulting in urban CO_2eq emissions that do not achieve neutrality prior to 2100 and only reaching a maximum value in 2060.

Figure 3d shows SSP2 results for the RCP value of 4.5 W/m^2. With a similar urban population profile to SSP4 at the global level, the urban emission results are driven by an urban per capita CO_2eq profile intermediate between the RCP 3.4 and 6.0 W/m^2 and hence a peak in global urban emissions approximately ten years before the GCAM SSP4 6.0 scenario (Figure 3e).

Figures 3f and 3g present the SSP3 and SSP5 scenarios, respectively. These are linked to the largest RCP values of 7.0 and 8.5 W/m^2. Unlike all other scenarios, these show increases in the urban per capita CO_2eq emissions combined with moderate urban population levels. This results in the highest urban CO_2eq emissions of the scenario set with urban emissions reaching about 8 times 1990 values in the REMIND MAGPIE SSP5 8.5 scenario by the end of the century.

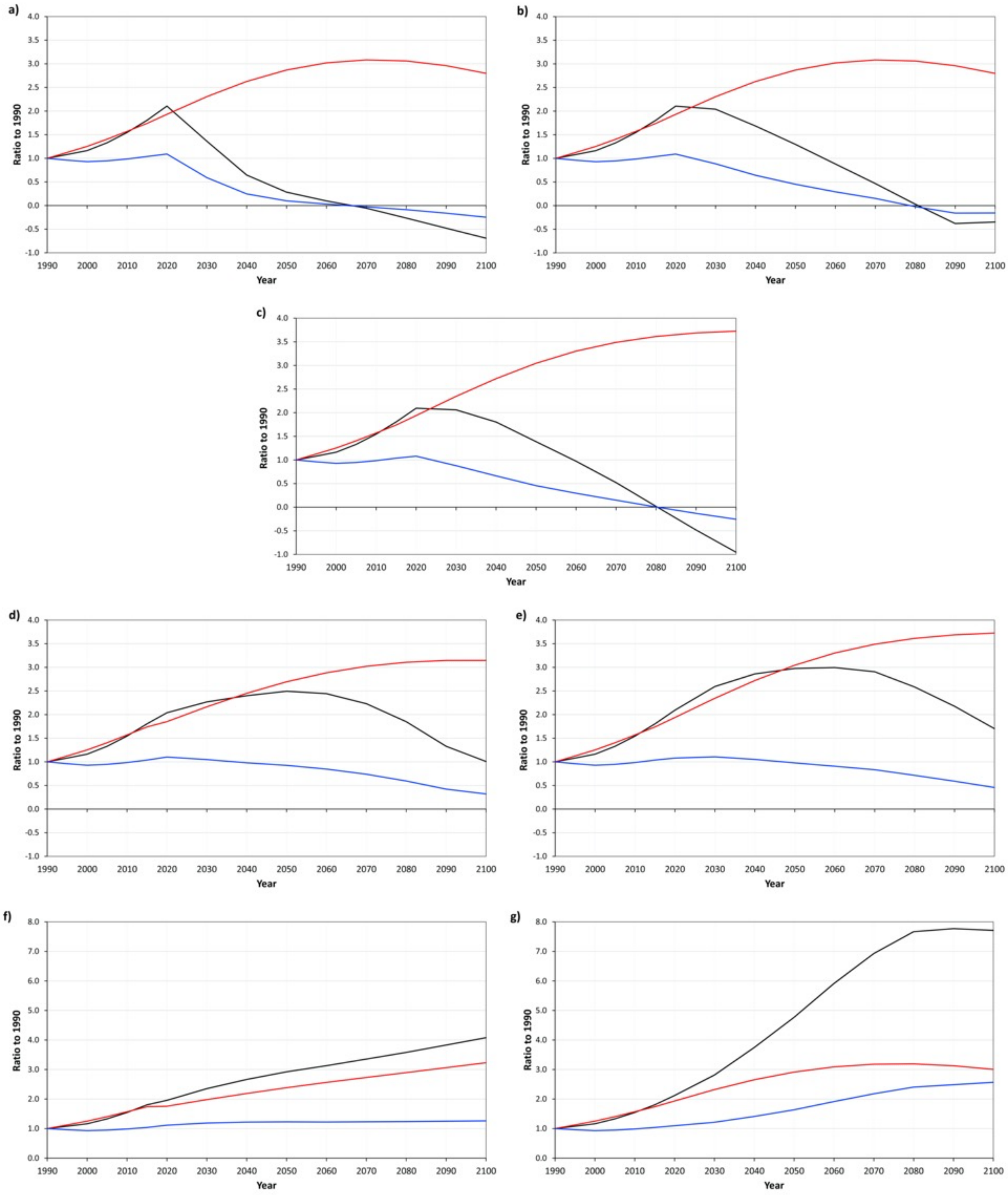

Figure 3. *Urban CO_2eq emissions aggregated to the globe (black line) with the two key drivers: urban population (red) and urban per capita CO_2eq (blue) where (a) IMAGE SSP1-1.9-SPA1, (b) IMAGE SSP1-2.6-SPA1, (c) GCAM4 SSP4-3.4-SPA4, (d) MESSAGE-GLOBIOM SSP2-4.5-SPA2, (e) GCAM4 SSP4-6.0-SPA4, (f) AIM SSP3-7.0-SPA0 and (g) REMIND-MAGPIE SSP5-8.5. Note that the y-axis scale on 3f and 3g is different from other panels. The underlying data are provided in supplementary information.*

3.3. Urban emissions to 2100

Figure 4 subdivides the global urban CO_2eq emissions into the 5-region aggregates and places them within the context of the global total CO_2eq emissions. In the first three scenarios (Figures 5a-5c) with more stringent reduction pathways and RCP targets, the share of urban CO_2eq emissions on an annual basis rises to values ranging from 84% to 100% of the global total CO_2eq emissions by 2100 (the 100% urban share values are an artifact of the passage from positive to negative global CO_2eq emissions). Furthermore, all three scenarios require negative emissions with a crossing point in the last two to three decades of the century. These negative emissions are dominated by the Developed Countries. In the SSP1-1.9-SPA1 scenario, for example, the urban emissions in all regions peak in 2020 at 28.6 GtCO_2eq accounting for 71.4% of the global total at that point in time. Net-zero GHG emissions are reached around 2065 followed by negative emissions, particularly for the Developed Countries region with a sizeable contribution from the Asia and Developing Pacific region in SSP1-1.9-SPA1 and SSP4-3.4-SPA4.

The SSP1-1.9-SPA1 shows the most precipitous urban emissions decline at 0.64 GtCO_2eq/year between the peak in 2020 and the zero-crossing point around 2065. In comparison, the decline in SSP1-2.6-SPA1 is about 0.48 GtCO_2eq/year until the zero-crossing point later in the century. In contrast, urban emissions under the SSP4-3.4-SPA4 scenario have the overall largest absolute decline of 41.3 GtCO_2eq between the maximum and minimum of emissions, owing to its larger negative emissions value at the end of the century.

The next two scenarios, SSP2-4.5-SPA2 and SSP4-6.0-SPA4, also show declines over the course of the 21st century but with a peak emissions coming later (34.0 GtCO_2eq in 2050 and 40.7 GtCO_2eq in 2050, respectively) and never crossing zero. The urban share is 71.9% and 82.4% at the end of the century, respectively. The peak emissions in all regions occur just after the mid-century mark except for the Africa and Middle East region, which delays the peak emissions by two decades.

The final two scenarios, SSP3-7.0-SPA0 and SSP5-8.5, show an urban share of 63.1% and 77.0%, respectively, by the end of the century accompanied by a much higher RCP value. This results in emissions increasing through nearly all decades of the 21st century (SSP5-8.5-SPA2 shows peak emissions in 2080 with a slight decrease in 2100). Urban emissions for the SSP3-7.0-SPA0 and SSP5-8.5 scenario reach 53.8 GtCO_2eq and 98.8 GtCO_2eq, respectively.

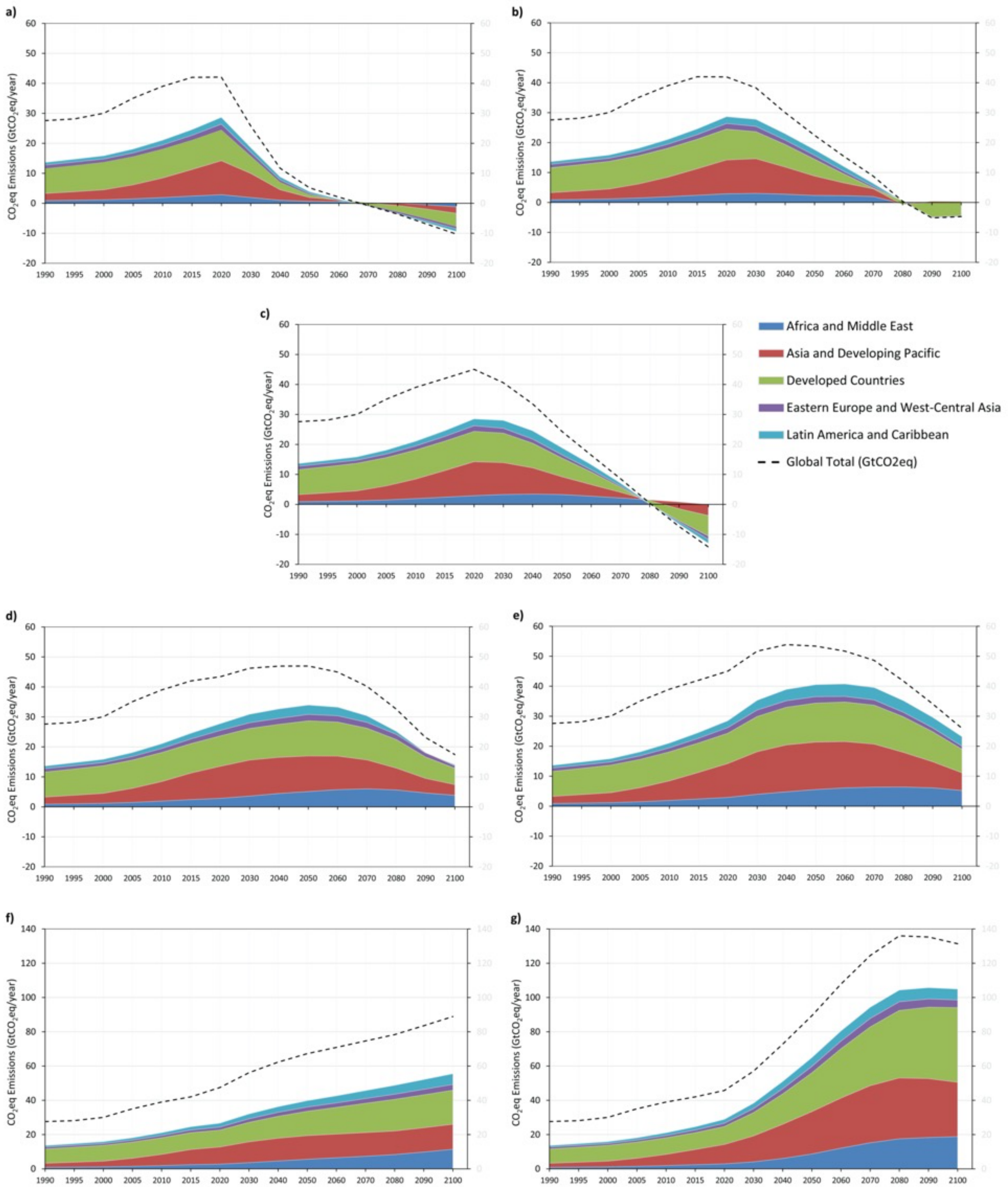

Figure 4. *CO_2eq emissions from urban areas in seven Model/SSP/RCP variations spanning the 1990 to 2100 time period where (a) IMAGE SSP1-1.9-SPA1, (b) IMAGE SSP1-2.6-SPA1, (c) GCAM4 SSP4-3.4-SPA4, (d) MESSAGE-GLOBIOM SSP2-4.5-SPA2, (e) GCAM4 SSP4-6.0-SPA4, (f) AIM SSP3-7.0-SPA0 and (g) REMIND-MAGPIE SSP5-8.5. Urban areas are aggregated to 5 regional domains. Global total CO_2eq emissions are shown based on the dashed line. Note that the y-axis scale of the 4f and 4g are different from the other panels. The underlying data are provided in supplementary information.*

4. Discussion

Based on the increasing dominance of the consumption-based CO_2eq emissions impact of urban areas across all the scenarios, mobilizing urban emissions reductions within the next decade will be instrumental for achieving climate targets. Figure 5a provides a comparison of the total annual urban emissions across the seven scenarios while Figure 5b shows the emissions changes projected by the scenarios between 2020 and 2030. Based on Figure 5b, lack of progress (SSP5-8.5) would result in a near-term increase in CO_2eq emissions of 9.7 GtCO_2eq. Moderate progress (SSP2-4.5-SPA2) would allow for a near-term increase in emissions of about 3.4 GtCO_2eq. Aggressive progress (SSP1-1.9-SPA1), by contrast, would result in a 9.8 GtCO_2eq decline in urban emissions and has been identified with the reduction level necessary to stay within a warming of 1.5 °C relative to pre-industrial levels (Rogelj et al., 2018; Tebaldi et al., 2021).

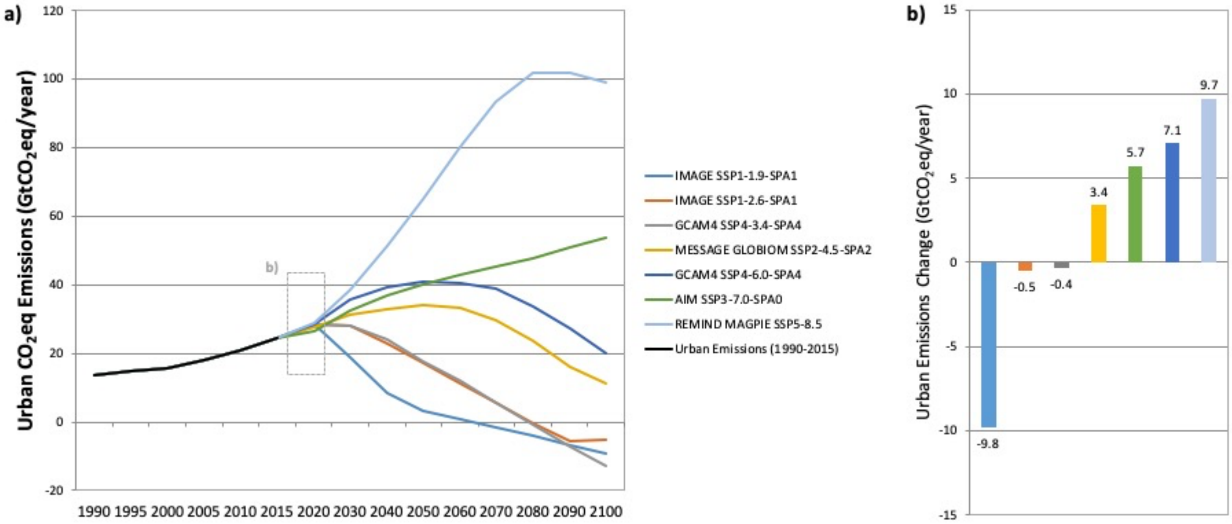

***Figure 5**. Comparison of the total annual urban emissions across the scenarios (a) and the change in absolute emissions between 2020 and 2030 (b) in GtCO_2eq per year. The underlying data are provided in supplementary information.*

4.1 Implications for urban mitigation

Considering that urban areas represent a large and increasing share of global GHG emissions, the outcomes of climate mitigation action will be largely contingent upon the contribution that urban areas can make to global reductions. These implications are summarized in Table 3. The urbanization typology are based on Jiang and O'Neill (2017) while the adoption rates of the urban emissions mitigation approaches are synthesized based on the marker model implementations of SSP1-SSP5. This will require contributions from both high emitting urban areas as well as urban areas that are yet to be planned and constructed to accommodate increases in the urban population. Trends established in the next decade following SDG11 criteria and its interlinkages (Kabisch et al., 2019) can also continue to provide benefits for more sustainable urbanization throughout the century. The way that urban areas are designed, built, and managed in all regions will determine resource usage patterns, material demands, energy choices, and co-benefits for urban inhabitants such as air quality (Fujimori et al., 2020) for much longer periods of time.

Table 3. *Synthesis of the urbanization typology and adoption levels in urban emissions mitigation approaches for the SSP-RCP framework*

<table>
<tr><th rowspan="2">SSP-RCP Scenarios</th><th rowspan="2">Urbanization Typology</th><th colspan="6">Urban Emissions Mitigation Approach</th></tr>
<tr><th>Electrification (a)</th><th>Energy and material efficiency[†] (b)</th><th>Technology development / innovation (c)</th><th>Renewable energy preferences (d)</th><th>Behavioral, lifestyle and dietary responses[‡] (e)</th><th>Afforestation and re-forestation (f)</th></tr>
<tr><td rowspan="2">SSP1
RCP1.9
RCP2.6</td><td rowspan="2">Resource efficient, compact and sustainable, rapid urbanization</td><td>Highest/ High</td><td>Highest/ High</td><td>Highest/ High</td><td>Highest/ High</td><td>Highest/ High</td><td>Highest/ High</td></tr>
<tr><td colspan="6">Implications for urban climate mitigation include:
→ Electrification across the urban energy system while supporting flexibility in end-use (a, d)
→ Resource efficiency from a consumption based perspective with cross-sector integration (b)
→ Knowledge and financial resources to promote urban experimentation and innovation (c)
→ Empowerment of urban inhabitants for reinforcing positive lock-in for decarbonization (a-f)
→ Integration of sectors, strategies and innovations across different urban areas in all regions
→ Compact urban form for sustainable urbanization with sustainable development co-benefits</td></tr>
<tr><td>SSP2
RCP4.5</td><td>Moderate progress</td><td>Medium</td><td>Medium</td><td>Medium</td><td>Medium</td><td>Medium</td><td>Medium</td></tr>
<tr><td>SSP3
RCP7.0</td><td>Slow urbanization, poor urban planning</td><td>Medium</td><td>Low</td><td>Low</td><td>Medium</td><td>Low</td><td>Low</td></tr>
<tr><td>SSP4
RCP 3.4
RCP6.0</td><td>Rate of urbanization differs with inequalities</td><td>Mixed</td><td>Mixed</td><td>Mixed</td><td>Mixed</td><td>Mixed</td><td>Mixed</td></tr>
<tr><td>SSP5
RCP8.5</td><td>Rapid urbanization with carbon lock-in (*)</td><td>High (§)</td><td>Low</td><td>High (§)</td><td>Low</td><td>Low</td><td>-</td></tr>
</table>

[†] Based on autonomous energy efficiency improvement related to the reduction in energy intensity over time considering reasons that are not related to energy prices and the intermediate input of materials decrease rate that relates to the rate at which such intermediate inputs as steel, non-metal and minerals, including cement, are decreased in production sectors.

[‡] Dietary responses reflect preference for less meat-intensive diets. Information is synthesized from marker model descriptions.

[§] Electrification and technology development is indicated to be high although strongly representative of carbon lock-in.

Within SSP1, the SSP1-1.9-SPA1 scenario requires the greatest mitigation contribution of urban areas in meeting a net-zero emissions target. In order to meet such rapid reductions, GHG emissions per capita would need to diverge significantly from increases in urban population. This, in turn, would require deep decarbonization based on renewable energy sources which could potentially increase co-benefits for the health and well-being of urban inhabitants. Alongside decarbonization, reductions of this magnitude would also likely require reductions in urban extent growth to reduce energy use, support from urban nature-based solutions to increase co-benefits, limitations on use of materials, and behavioral changes of urban consumers.

Based on the narrative of this scenario, urbanization under SSP1 takes place rapidly across all countries driven by environmentally-friendly urban living and resource efficiency derived from compact urban form (Jiang and O'Neill, 2017). In the context of a green growth paradigm, there is rapid technological development and improved efficiency, sharp increases in the share of renewable energy with high learning rates and low integration costs as well as rapid electrification with a high share of electric transport (van Vuuren et al., 2017b). These trends take place alongside investments in education and human development that reduce increases in population as well as pressures on land use with additional strong regulations. The focus of the policy framework is on global cooperation that further supports cost-optimal solutions for resource efficiency. There is lower intensity for the demand of cement and steel (van Vuuren et al., 2017b), which implies changes in the material demands for urban infrastructure development. Overall, SSP1 reflects a major shift to resource-efficient, compact and sustainable urbanization around the globe on the path towards sustainable development. Such a scenario would require the most significant shift in the trends over the last decades as well as a reversal of declining urban densities across regions and income levels as observed in (Güneralp et al., 2020). It would further require implementing compact urban form in new urban areas and upscaling an integrated mix of solutions, including those for decarbonizing the electricity supply, realizing deep energy savings and supporting behavioral change (Goldstein et al., 2020). In addition, concerns for the impacts of the pandemic on urban form and spatial planning would need to be overcome while ensuring that the co-benefits of urban infrastructure for wellbeing can be maximized.

In contrast, SSP2 depicts a future that more closely builds upon - but is not a direct extrapolation of - existing trends (Fricko et al., 2017). Improvements in energy intensity more closely represent continued advances that are not markedly different than existing trends in energy efficiency, technology development, as well as behavioral and lifestyle preferences (Fricko et al., 2017). Convergence across regions based on socio-economic and technological development is moderate. Increases in the electrification rate in residential and commercial buildings as well as transport are at medium levels and there are moderate levels of renewable energy exploitation (Fricko et al., 2017). One of the characteristics of the SSP2 marker scenario is the surge in final energy demand in both developed and developing countries with a quadruple increase in the latter (Fricko et al., 2017). This has implications for the ability of urban development to manage increases in final energy demand although urbanization under SSP2 proceeds at a moderate pace (Jiang and O'Neill, 2017). In this context, it is envisioned that there would be moderate co-benefits with SDG thresholds only being possibly met, including those for SDG11. Moreover, it is estimated that the stock of materials in the construction of residential buildings will double by 2050 under SSP2, including concrete, steel, and aluminum. Such an increase is attributed largely to residential buildings in urban areas (Marinova et al., 2020).

Urbanization under SSP3 is slow across all countries of the world due to poor urban services and spatial planning and subsequent limited migration (Jiang and O'Neill, 2017). SSP3 involves regional rivalry that is accompanied by large population increases and lagging income growth (Fujimori et al., 2017). Energy outcomes include a slow advance in renewable energy cost reductions due to slow technological development with a medium electrification rate (Fujimori et al., 2017). This implies similarly low levels of such opportunities in urban areas. There are also limited reductions in intermediate material inputs, including steel (Fujimori et al., 2017) such as would be used for urban infrastructure development. In addition, low levels of improvement in emissions and energy intensity lead to weak levels of air pollutant emissions control (Fujimori et al., 2017) that would have impacts on the health and well-being of urban inhabitants. SSP3-7.0-SPA0 represents an increase of 5.7 $GtCO_2eq$ in 2030 over 2020 levels (Figure 5) without setting broader trends for sustainable urbanization into motion.

SSP4 represents a mixture of urbanization paces where moderate rates of urbanization occur in the high-income countries and rapid rates of urbanization occur in the middle and low-income countries (Jiang and O'Neill, 2017). Moreover, aspects of inequality not only take place across regions but also within urban areas, including inequalities between the urban elite and urban inhabitants in informal settlements (Jiang and O'Neill, 2017). In this context, SSP4 represents stark inequalities within and across regions. There is prosperity in high-income regions with continued growth in electrification while low-income regions stagnate with increases in population rather than increases in energy per capita driving the emission increases (Calvin et al., 2017). Energy demand due to increases in per capita floor space is limited due to saturation in high-income countries versus stagnation in low-income countries. While the preference for renewables is high across countries, implementation is constrained by apparent inequalities and progress on technology development (Calvin et al., 2017). Another aspect is regional afforestation versus deforestation in different income levels with no land policy in low-income countries (Calvin et al., 2017).

Such a narrative has ramifications on urban areas, including limitations on the benefits that urban areas can provide for increased access to electricity (Aklin et al., 2018) and other basic human needs, including food, water, sanitation and health care for the vulnerable. Another ramification is the inability of urban planning to address distributional aspects among the urban population, including lack of policies to simultaneously address energy poverty and climate mitigation (Colenbrander et al., 2016) as well as solutions that avoid possible green gentrification (Padeiro et al., 2019). Limited co-benefits are envisioned for this scenario with SDG11 and related SDGs mostly not being met across the urban areas of the world despite different RCP levels. By 2030, urban emissions are estimated to reduce by 0.4 $GtCO_2eq$ in SSP4-3.4-SPA4 and increase by 7.1 $GtCO_2eq$ in SSP4-6.0-SPA4 over the 2020 levels of these scenarios while not addressing broader societal concerns.

Urbanization under SSP5 takes place rapidly across all countries of the world based on the ability of urban areas to attract residents due to high economic growth and technological change (Jiang and O'Neill, 2017). Like SSP1, this scenario involves rapid urbanization across all regions but under different conditions. Technological change under SSP5 leans towards large-scale engineering projects and technological improvements in agriculture that increases migration to urban areas (Jiang and O'Neill, 2017). In addition, SSP5 involves both rapid energy and material-intense fossil-fuel development. Global food demand is doubled based on high meat-based diets and greater amounts of food waste with implications for land use (Kriegler et al., 2017). In addition to large amounts of waste, energy demand is tripled with both high energy intensity in transport and medium energy intensity in buildings without resolving carbon lock-in (Kriegler et al., 2017). This would similarly correspond to energy intense and fossil fuel-based modes of transport in urban areas, particularly car dependency, as well as high CFs across global supply chains. Another aspect is the peaking of natural gas supply as late as 2070 that is used in the energy mix for electrification as well as space heating (Kriegler et al., 2017), which represents a persistent carbon lock-in for urban energy supply (Seto et al., 2016) with additional ramifications for CH_4 emissions (Riahi et al., 2017). Moreover, SSP5 assumes low public acceptance and policy support for renewable energy. While the world is set to reach income convergence among regions at the end of the century in SSP5, such risks as undernourishment and other concerns remain (Kriegler et al., 2017) that would also imply failures to address basic human needs in urban areas.

Against these consequences, urban emissions are estimated to increase without any mitigtion in the near-term by 2030 with continued increases across the rest of the century (Figure 5). Overall, the baseline of the SSP5 scenario leads to the worst outcome with a corresponding global mean temperature increase greater than 5°C (Kriegler et al., 2017) under the assumed climate sensitivities. For this reason, the SDGs would not be met considering the severe impacts of climate change that would be felt under this scenario.

Across the scenarios, aspects of technology development as well as their penetration within the energy system are among the key energy-related uncertainties (van Vuuren et al., 2011). In this context, urban areas can reinforce positive trends in technology development acceleration and innovation for climate mitigation as well as lifestyle changes that can support attaining positive lock-in (Ürge-Vorsatz et al., 2018). Taking advantage of the urban demand to provide flexibility in energy systems with a high penetration of renewable energy for deep decarbonization can be shaped with urban policies, including policies that target net-zero emissions (Seto, K. C., 2021). Urban areas can also be innovation hubs for upscaling niche solutions that are important for green growth sustainability paradigms. For the realization of such paradigms, positive correlations between urbanization levels and economic growth (Chen et al., 2014) would need to be decoupled from consumption pressures, including through behavioral and lifestyle changes. The proximity of actors in urban areas (Lee and Erickson, 2017) as well as urban experimentation (Peng and Bai, 2018) is further known to have a positive effect on technology diffusion and adoption. The ability to steer urban areas towards sustainability based on renewable energy, resource efficiency and compact urban form across the regions of the world in a coordinated way will be a key aspect for reaching net-zero emissions with sufficient pace and timing for climate mitigation.

Based on the suite of urban mitigation strategies, scenarios with the same rapid, moderate, mixed, or slow urbanization rates are found to have different urban emission outcomes (see supplementary information). Especially in the scenarios that involve rapid urbanization, some countries will experience significant increases in the urban population share. This includes India and Uganda where increases in the urban population share are projected to increase by 51.1% and 67.0%, respectively between 2020-2100 under rapid urbanization (Jiang and O'Neill, 2017). Such population share increases, however, will have starkly different outcomes in scenarios with and without carbon lock-in during the same timeframe (see Figure S1). For example, while India will have lower urban emissions in 2100 than in 2020 under the SSP1-1.9-SPA1 and SSP1-2.6-SPA1 scenarios, the change in urban emissions over the same time period will be about 11.7 $GtCO_2eq$ in SSP5-8.5. Given rapid urbanization under both scenarios across all regions of the world, major transformations in new urban areas can avoid the negative consequences of the latter scenario. Other scenarios that involve moderate, mixed, and slow urbanization rates also represent differences. Urban mitigation policy has a pivotal role in constraining emissions on an annual basis and within remaining budgets.

4.2 Cumulative urban emissions

Based on the above results and discussion, the cumulative sum of annual urban emissions provides additional insight on the urban emissions share in relation to longer-term climate targets. Figure 6 provides net cumulative emissions from 2020 onward for urban and/or rural areas in the context of the total global cumulative emissions for each scenario. Such a comparison is also relevant given that decisions regarding urban form and infrastructure can contribute to cumulative reductions or increases over longer periods of time. The top panels (Figure 6a,b) represent scenarios that achieve net-zero emissions within this century while the bottom panel (Figure 6c,d) represents scenarios that do not.

The minimum and maximum cumulative urban emissions in 2100 across the scenarios in the top panel range between 293.8 $GtCO_2eq$ and 922.4 $GtCO_2eq$. The urban share of the cumulative global total ranges between 66.6% (SSP1-1.9-SPA1) and 75.4% (SSP1-2.6-SPA1). Rural areas have shares of, at most, 33.4% by 2100 (Figure 6). In comparison, the minimum and maximum cumulative urban CO_2eq emissions in scenarios without net-zero emissions crossing points ranges between 2,218.9 $GtCO_2eq$ (SSP2-4.5-SPA2) and 6,021.8 $GtCO_2eq$ (SSP5-8.5). The urban share of the cumulative global total emissions ranges between 62.6% (SSP3-7.0-SPA0) and 79.6% (SSP4-6.0-SPA4) while those of rural areas have shares of, at most, 37.4%.

Urban areas would need to achieve large savings in cumulative urban emissions close to the thickness of the wedges in Figure 6a and 6c in order for the globe to achieve the target of staying within 1.5°C of warming above pre-industrial levels (lower bound in Figure 6a). Moreover, the role of resource efficient and compact urban areas would be particularly significant for driving the reductions that are associated with this most stringent climate mitigation scenario. Despite the rapid urbanization in this scenario, cumulative urban CO_2eq emissions (orange circle in Figure 6b - 293.8 $GtCO_2eq$) are 7.6 times lower than the cumulative urban CO_2eq emissions of the moderate scenario with moderate rates of urbanization (SSP2-4.5-SPA2 in Figure 6d – 2218.9 $GtCO_2eq$).

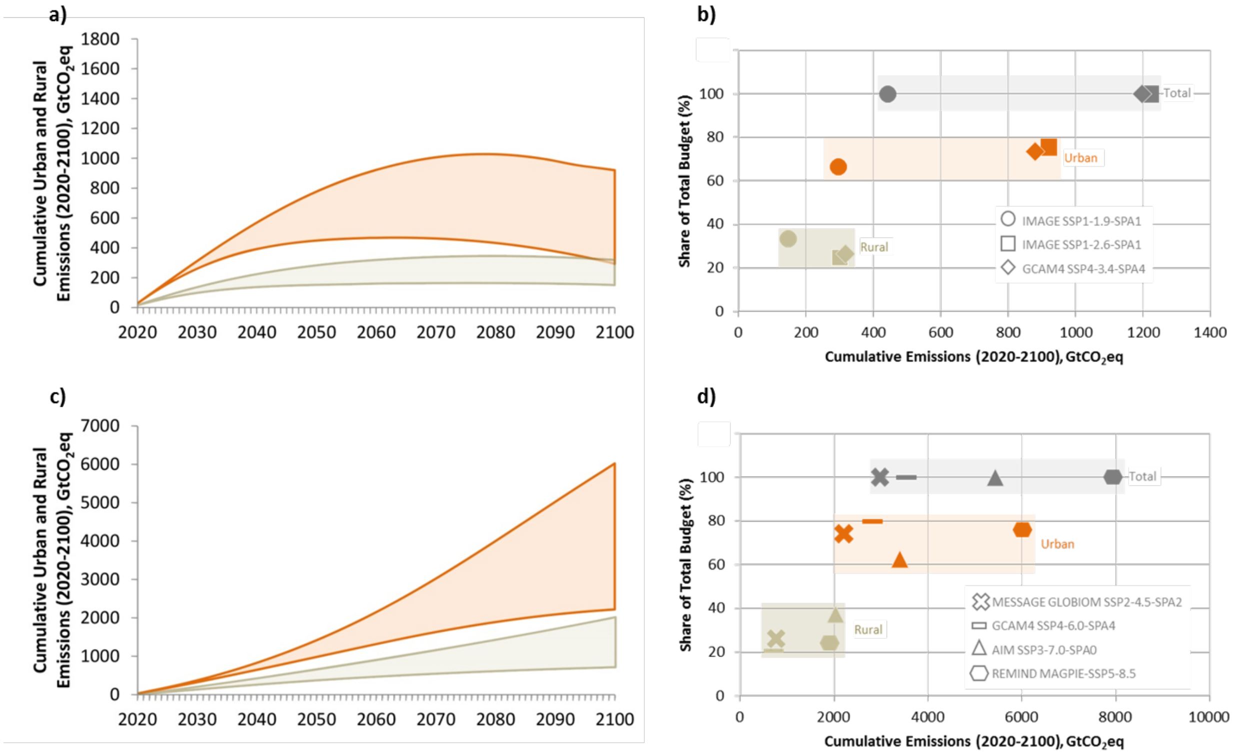

***Figure 6**. Global cumulative (between 2020-2100) urban CO_2eq emissions for scenarios that achieve net-zero CO_2eq emissions (top) and those that do not (bottom) within this century. Orange shaded areas represent the minimum and maximum values of cumulative urban emissions in the three* SSP-RCP-SPA *scenarios that achieve net zero emissions (a) and the four scenarios that do not (c). Cumulative rural (beige shaded areas and markings) and total cumulative emissions (grey colored markings on the right) are given for comparison. Note:the*

y-axis scale on panels a) and c) and the x-axis scale on panels b) and d) are different. The underlying data are provided in supplementary information.

Under different conditions and continued lock-in, rapid urbanization in SSP5-8.5 leads to total cumulative emissions that are about 2.7 times larger than the cumulative emissions of the moderate scenario (SSP2-4.5-SPA2). In contrast, differences in the cumulative emissions of rural areas across scenarios are considerably smaller. Due to relatively steadier dynamics across time, the maximum values of cumulative rural emissions in scenarios with and without net-zero emission crossing points respectively, range between 317.1 $GtCO_2eq$ and 2031.8 $GtCO_2eq$ during the same timeframe.

Figure 7a plots the share and magnitude of cumulative urban emissions on a regional basis. The regional share of cumulative urban emissions has the highest variation across the scenarios for the Asia and Developing Pacific region (span: 18.4%) and the Developed Countries region (span: 14.7%). The Asia and the Developing Pacific region also have the greatest share of cumulative urban emissions in SSP1-1.9-SPA1 (52.9%) and when combined with the Developed Countries region, accounts for 65.0-73.3% of the cumulative regional share of the urban emissions budget across the scenarios.

The timing of net-zero urban emissions shows a similar division when expressed in combination with the cumulative emissions budget (Figure 7b). The Asia and Developing Pacific and Developed Countries regions both show early net-zero crossing times combined with large cumulative CO_2eq emission budgets. This emphasizes both the large increase in emissions in these regions and the policy focus in reducing these regional emissions rapidly. In contrast, urban areas in two regions (Africa and Middle East, Eastern Europe and West-Central Asia) have a difference of more than 20 years in reaching net-zero CO_2eq emissions.

At a global level, annual urban emissions reach net-zero emissions by 2064 under the SSP1-1.9-SPA1 scenario. The peak cumulative urban emissions between 2020 and this net-zero emissions year is 468.2 $GtCO_2eq$. In comparison to the cumulative urban emissions under the next scenario that is representative of the 2°C pathway based on known climate sensitivities (SSP1-2.6-SPA1), such a budget would be consumed about 28 years earlier in 2036 given that 469.8 $GtCO_2eq$ of cumulative urban emissions would be reached under this scenario. Other scenarios further suggest that the cumulative urban emissions budget for SSP1-1.9-SPA1 up to the net-zero year would already be exceeded as early as the year 2033 excluding negative emission options. These findings underline the crucial importance of the next decade and a half in setting and realizing the trends that can direct urban areas to remain within the bounds of a safe and just planet.

These comparisons further underline the importance of urban areas in general and the Asia and Developing Pacific and the Developed Countries regions, in particular, in driving and enabling effective climate mitigation.

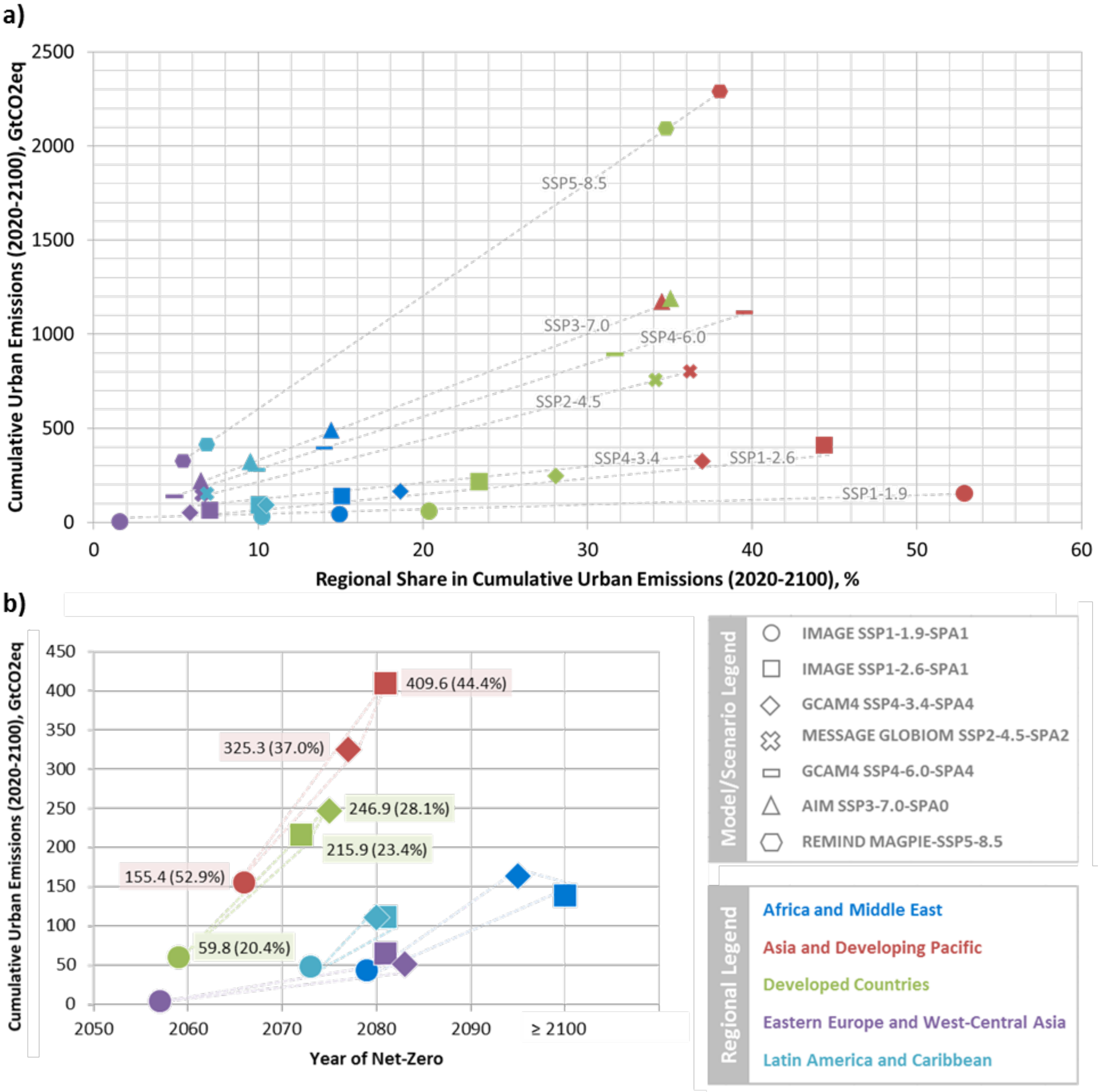

***Figure** 7. Regional cumulative (between 2020-2100) urban CO_2eq emissions and regional share of cumulative urban emissions for all scenarios (a). Regional cumulative (between 2020-2100) urban CO_2eq emissions and the timing of the net-zero CO_2eq emissions crossing point for selected scenarios (b). Symbol shape denotes scenario, color denotes region (see legend). Light dotted connecting lines are included for guidance in locating scenarios or regions. The underlying data are provided in supplementary information.*

5. Conclusions

There has been limited analysis to date on how the urban portion of global emissions is quantitatively related to scenario projections of global emissions. Because the current share of global emissions in cities worldwide is large (~70%), the expectation is that this share will continue to grow placing a greater emphasis on urban areas as locations where GHG emissions mitigation must occur. This study attempts to fill that knowledge gap by explicitly quantifying urban CO_2eq emissions in the SSP-RCP-SPA framework, used by the research community to understand the possible future emission conditions. Using existing data and assumptions about changes in per capita CO_2eq urban emissions over time, we quantify urban CO_2eq emissions within seven SSP-RCP-SPA scenarios and five global regions, using the scenario storylines to develop a deeper understanding of how urban areas can mitigate GHG emissions. The narratives of the scenarios can also provide direction into achieving climate mitigation more sustainably.

The quantification of urban GHG emissions regionally and globally out to 2100 has specific significance for at least three reasons. First, quantifying urban emissions within the SSP-RCP-SPA framework can significantly enhance analytical support for decision-making at all levels and provide direction to the climate mitigation focus of urban areas. Second, a better understanding of this crucial portion of global emissions in each scenario can guide the differentiation of possible outcomes for urban emissions and mitigation according to different emission drivers and urban narratives. Third, the results of the research work can better support urban decision-makers by quantifying the implications of the outcomes of a wide spectrum of urban mitigation possibilities.

We find that the dominant driver in our estimation approach when combined with the SSP-RCP-SPA framework is the urban per capita CO_2eq value. In the near term, between now and 2030, a total decline of 9.8 $GtCO_2$eq would be required in urban areas necessary to stay within a warming of 1.5 °C relative to pre-industrial levels.

With the explicit identification of urban emissions regionally, narratives of urbanization are now matched with quantified urban emissions under each scenario with extended discussions on their implications for urban mitigation. Urban emissions under scenarios with the same urbanization rate can differ widely due to urban mitigation strategies. The urbanization typology has a central role in shaping the future of urban emissions. The rapid uptake of electrification, energy and material efficiency, technology development and innovation, renewable energy preferences, as well as behavioral, lifestyle and dietary responses in urban areas can contribute to more sustainable urbanization. A comparative view across the scenarios raises the need for coordinated action that encompasses electrification of urban energy systems, resource efficiency, compact urban form, and urban experimentation as well as their coherent integration for effective climate mitigation.

Examination of the cumulative CO_2eq emissions in each scenario and global region highlights the importance of the Asia and Developing Pacific and Developed Countries regions in both the overall urban emissions growth and in emissions mitigation. These two regions are key to all of the future emission scenarios and place emphasis on low-carbon pathways for these urban areas.

It is expected that this paper will provide the basis to explicitly include the urban emissions share within the global context in subsequent scenario results. This is vital for representing the role of urban areas in climate mitigation pathways as well as an increased focus on climate change and cities at the IPCC level. The study is also expected to stimulate a data-driven approach for sustainable urbanization pathways while enabling a consideration of increasing co-benefits for sustainable development. Future work will focus on further advancing the synthesis of relevant datasets as these may become available.

Supplementary Information

Original datasets and supporting information generated in this research work are represented in supplementary information.

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