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A global overview of developments of urban and rural household GHG footprints from 2005 to 2015

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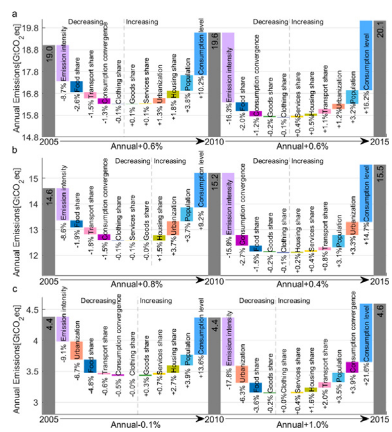
HIGHLIGHTS

- Differences between urban and rural HGFs are investigated.
- The ongoing consumption transition led to an emission pattern shift.
- Rural emissions are slowly converging with high urban emissions.
- High income regions drive 75% of household emissions.
- Urbanization contributed to an increase of HGFs of above 1% yr^{-1}.

GRAPHICAL ABSTRACT



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ABSTRACT

Household greenhouse-gas footprints (HGFs) are an important source of global emissions but can vary widely between urban and rural areas. These differences are important during the ongoing rapid, global, urbanization process. We provide a global overview of HGFs considering this urban-rural divide. We include 16 global regions, representing 80% of HGFs and analyze the drivers of urban and rural HGFs between 2005 and 2015. We do this by linking multi-regional input-output (MRIO) tables with household consumption surveys (HCSs) from 43 regions. Urban HGFs from high-income regions continue to dominate, at 75% of total HGFs over 2010–2015. However, we find a significant increase of rural HGFs (at 1% yr^{-1}), reflecting a convergent trend between urban and rural HGFs. High-income regions were responsible for the majority of urban HGFs (USA: 27.8% and EU: 18.7% in 2015), primarily from transport and services, while rural HGFs were predominately driven in emerging regions (China: 24% and India: 21.8% in 2015) mainly driven by food and housing. We find that improving emission intensities do not offset the increase in HGFs from increasing consumption and population during the period. A broad transition of expenditure from food to housing in rural areas and to transport in urban areas highlights the importance of reducing the emission intensities of food, housing, and transportation. Counterintuitively, urbanization increased HGFs in emerging regions, resulting in a >1% increase in China, Indonesia, India and Mexico over the period, due to large migrations of people moving from rural to urban areas.

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1. Introduction

Household consumption comprises >60% of global GHG emissions (Yuan et al., 2015; Ivanova et al., 2016). This varies by nation, from 80% in the USA (Jones and Kammen, 2011), 40% in China (Liu et al., 2011), 74% in the UK (Baiocchi et al., 2010), and 52% in the Republic of Korea (Park and Heo, 2007). Understanding household GHG footprints (HGFs), analyzing their characteristics and drivers, and exploring mitigation policies are prerequisites for promoting sustainable consumption (Hertwich and Peters, 2009; Chen et al., 2018; Palm et al., 2019).

Recent years have seen an increasing research interest in household emissions (Chen and Chen, 2011; Chen et al., 2013; Gonzalez-Hernandez et al., 2019; Xue, 2020). For instance, studies have focused on the driving factors of Indian emissions across different cities (Ahmad et al., 2015; Lee et al., 2021), Chinese regional emissions (Li et al., 2016; Shi et al., 2020; Zhang et al., 2020), Japanese regional emissions (Long et al., 2021) and European regional emissions (Castellani et al., 2019; Lévay et al., 2021; Salo et al., 2021). They found that household emissions play a fundamental role for implementing emission reduction policies. Research methods used to analyze HGFs primarily include the consumer lifestyle approach (CLA), input-output analysis (IOA), life cycle assessment (LCA), and emission inventories (EI), in the which IO models can comprehensively reflect the HGEs embedded in the products (Li et al., 2020; Zhou and Gu, 2020). However, these studies were conducted at the national and regional levels by examining HGFs at a disaggregated level. This cannot provide a comprehensive regional assessment by which to compare global trends. Wu et al. (2019) and Chen et al. (2019c) presented a global view of household energy use and found that the global household energy use was over one-fifth of the global total energy consumption in 2012. However, to our knowledge, a global perspective of HGFs and the urban-rural divide is lacking. It is important to provide a complete and consistent database in time and space of HGFs for a regional comparison of emissions patterns and driving factors of global HGFs for both urban and rural regions.

Previous studies have identified income level, population, and consumption structure as the main drivers of household emissions (Pablo-Romero et al., 2016; Christis et al., 2019; Zhao et al., 2021). For example, Girod and de Haan (2010) analyzed discussed the impact of lifestyle changes on emissions using a Swiss household consumption survey, they did not compare the difference in the impacts of consumption transitions on urban and rural HGFs. Wang and Yang, 2014, Wiedenhofer et al., 2016 and Wang et al., 2019 analyzed the impact of consumption transition on household emissions. Urbanization can also impact HGFs, for example, O'Neil et al. (2010) found that urbanization can substantially influence emissions, particularly in key regions of the world, including China, India, the United States, and the EU. Yuan et al. (2015) and Sheng et al. (2020) found that increasing urbanization in China resulted in increasing household emissions. This result has been seen in Germany (Gill and Moeller, 2018), Norway (Liu et al., 2020) and other Asian nations (Krey et al., 2012). Although there are numerous papers that have discussed the impact of urbanization on emissions (Liddle, 2014), they mainly use econometric models which do not provide specific numbers on the impact of urbanization worldwide.

Understanding urban-rural disparities in the drivers of HGFs are important because there is a large variation in urbanization across countries, which may lead to different emission profiles (Ponce de Leon Barido and Marshall, 2014; Kanemoto et al., 2014; Khosla et al., 2019). For example, the average annual urbanization in China and India was approximately 2.5% and 1.1% yr^{-1} from 2005 to 2017, respectively, while Japan's urbanization rate rose slowly over the same period, at an average annual growth rate of 0.5% yr^{-1} (United Nations, 2017). Another motivation for comparing the urban-rural disparities is the large differences in consumption patterns between urban and rural residents in emerging countries at different stages of the consumption transition ((Nie et al., 2018, Chen et al., 2019b, Wang and Chen, 2020). Urban residents typically consume more goods and services than rural residents (Wiedenhofer et al., 2013; Chen et al., 2019a; Cao et al., 2019). Ivanova et al. (2015) used the newly established EXIOBASE 2.2. MRIO database to describe the household environmental footprints of 43 countries in 2007, and found that the distribution of household environmental footprints is inequal, with wealthier countries emitting the largest impacts per capita. However, they did not assess and compare environmental impacts of household consumption between urban and rural areas across various regions. Also, they did not identify how urbanization would impact household GHG footprints across regions. There are also several studies combining the EXIOBASE MRIO (with 200 products level for each country) with household consumption surveys to assess household GHG footprint analysis at a very detailed income group level (Ivanova et al., 2017, Ottelin et al., 2019, Ivanova and Wood, 2020) and found that the emissions impacts of income vary among different consumption categories. However, these studies focused on the household carbon footprints in Europe and did not distinguish between emerging and advanced regions. How urban and rural HGFs vary across emerging regions compared to high-income regions and how they are moderated by consumption patterns remain an open question.

To address these issues, we disaggregate household consumption into urban and rural groups by combining household consumption survey (HCS) data for 43 nations with multi-regional input-output (MRIO) tables. Using these disaggregated data, we identified key contributing regions and products of urban and rural HGFs. Six product categories were included: food, clothing, housing, household appliances, transport and services. We then conduct a decomposition analysis to identify the contribution of emission intensities, consumption convergence (i.e., the difference between rural or urban per capita consumption and that of the average), consumption structure, urbanization, population and consumption level to the overall change in HGFs.

In contrast with the existing literature, which analyzed total household emissions at the national and regional levels, we not only provide a comprehensive picture of HGFs from a global perspective, but also distinguish the differences in HGFs between emerging and advanced regions. We also disaggregate total household consumption data into urban and rural areas with a complete and consistent database in time and space, which allows for a more detailed discussion on the distinctions of urban and rural emissions worldwide for a regional comparison. Further, using the MRIO model, we focus on the specific impact of urbanization and differentiate the impacts of consumption transitions on urban and rural HGFs.

The rest of the paper proceeds as follows. In Section 2, we present methods and information on the data. Section 3 provides the results. Section 4 presents discussion and Section 5 concludes the paper.

2. Methods and data

2.1. Data sources

In this study, data for MRIO tables and emissions are from version of EXIOBASE 3 (Wood et al., 2015; Stadler et al., 2018). In EXIOBASE 3, MRIO tables have been released for the period 1995–2015, and are available for 49 regions. Due to the limitation of household consumption data, we only focus on two selected periods, 2005–2010 and 2010–2015, and 43 regions. Switzerland and the Rest of World are excluded. The period from 2005 to 2010 witnessed a rapid decline in the share of HGFs in total global GHGs, from 59% to 55%. During 2010 to 2015, the share of HGFs in the global GHGs slowly dropped further to 54%. The 43 regions we examine together represent about 80% of global HGFs. For ease of presentation, we aggregate results for 28 EU's members into 1 region called EU (see Table S1). Thus, 16 regions in total are analyzed in this paper. Household consumption is drawn from EXIOBASE 3 considering 200 products in monetary units. Since we analyze six main consumption activities (based on the COICOP classification), we aggregate the 200 products in the MRIO tables into 6 product categories (see Table S2). The six main product categories are food, clothing, housing, household appliances, transport and services. Data for population are from the UN (United Nations, 2017).

We collected urban and rural household consumption data from 43 regions' household consumption surveys (HCSs) and disaggregated household consumption in the EXIOBASE into the 2 groups (urban and rural), see Table S3 and supplementary data. Since some regions do not have HCSs for specific years, we used neighboring years for Canada (2005), Australia (2005 and 2010), Mexico (2015) and South Africa (2015). For example, Canada did not publish a 2005 HCS, but did the following year, so we use 2006 as a proxy for 2005. Brazil (2005), India (2015) and Turkey (2015) had no data in a neighboring year so we followed World Bank recommendations (The World Bank, 2012) and linearly interpolate, such that all urban/rural household consumption data can be obtained in a benchmark reference year, 2005, 2010 and 2015 (see Table S1). For Denmark (2015) and France (2015), Malta (2010 and 2015) and Norway (2015) we only had one observation, so interpolation was not possible. We used the data for neighboring nations with similar economic levels, culture and geographic location. For example, for Malta, we used the consumption data for Italy. For further details of this interpolation see Table S4.

Before Linking IO tables and household consumption data, we first convert the EXIOBASE dataset and HCS dataset into 2010 constant prices with price indexes. EXIOBASE does not provide PYP deflators, so these were taken from the WIOD database and UN (the details for estimates for deflators can be seen Supplementary materials).

2.2. Estimation of household GHG emissions

Input-output analysis is a common method for estimating HGFs (Davis and Caldeira, 2010; Fauré et al., 2019). Following Wei et al. (2007), we calculate HGFs by multiplying the monetary expenditure in each product category by their respective emission intensity of a consumed product by households. To estimate the emission intensity of a consumed product by households, we first use the Leontief inverse to calculate the emission intensity of a product i manufactured in region r, M_i^r, taking into account all emissions that occur along the supply chain to deliver one unit of product is calculated as: (Miller and Blair, 2009):

$$M = B'L \tag{1}$$

where M is a vector in which M_i^r is the emission intensity of a product i manufactured in a region r. B is the vector of direct emission coefficients, whose corresponding entry is $B_i^r = R_i^r/X_i^r$, the ratio between direct emissions and total output of that activity sector. L is the Leontief inverse, in which L_{ij}^{rs} expresses how much the consumption of one unit of product j in region s stimulates the total output of sector i in region r.

To obtain the emission intensity of a consumed product by households,
F_i^r from M_i^r, it is necessary: to aggregate over products, since the original MRIO has 200 products and in this paper only 6 are considered; average over imported regions, since in F_i^r only the region of household consumption is specified while the region defined in M_i^r is the region of manufacture; deflate to a benchmark year; and allocate direct emissions of household consumption, Ed_i^r, to the household consumption of specific products. We perform these steps using the following expression:

$$C_i^r = \frac{Ed_i^r + \sum_j \sum_s U_{ij}^{pro} M_i^s Hcurr_j^{sr}}{\sum_j \sum_s U_{ij}^{pro} Hconst_j^{sr}} \tag{2}$$

where U_{ij}^{pro} is a product aggregation matrix, which is 1 if aggregate sector i (in the 6 sectors list used in Table S2) corresponds to disaggregate sector j (in the 200 sectors list of EXIOBASE) and 0 otherwise. The denominator therefore represents the total household expenditure in the aggregate product category in constant prices. The numerator is the total volume of embodied emissions in that same aggregate product category, whose supply chain emissions are obtained by multiplying intensities with monetary volumes in current prices. The numerator also contains the direct emissions of household consumption that were allocated to particular product categories.

Then, introducing the household consumption expenditure of product i in the region r (H_i^r), we calculate total HGFs as:

$$E = \sum_r \sum_i C_i^r \cdot H_i^r \tag{3}$$

2.3. Linking MRIO tables and household consumption data

To link the MRIO with HCSs we allocate household consumption in a region to respective urban and rural areas and construct a final consumption matrix for urban and rural households. This matrix describes the urban and rural household expenditure at a detailed level based on the COICOP classification. The matrix is compiled from the original final demand vector available in the MRIO table, but then altered to reflect urban and rural household consumption using HCS data for 43 regions. We do this through several steps:

We first divide the total household consumption into urban and rural consumption using the information on per capita urban/rural consumption derived from the HCSs. It is important to harmonize between HCS and MRIO sources because there are statistical differences in their collation. This includes ensuring that the sum of urban and rural household consumption from HCS data equals the total household consumption from MRIO tables. We did not directly use the absolute consumption per capita to disaggregate the total household consumption. We use data for urban/rural consumption per capita to estimate the urban-rural ratio d, and then use this to estimate the urban and rural per capita household consumption as:

$$d = \frac{M^{urb^*}}{M^{rur^*}} \tag{4.1}$$

$$M^{rur} = \frac{H}{d \cdot P^{urb} + P^{rur}} \tag{4.2}$$

$$M^{urb} = M^{rur} \cdot d \tag{4.3}$$

where H is the total regional household consumption in the MRIO; M^{urb^*} and M^{rur^*} are the original per capita household consumption values for the urban and rural area in a region obtained from HCSs, respectively; P^{urb} and P^{rur} are the urban and rural population in a region, respectively; M^{urb} and M^{rur} are the adjusted per capita household consumption for the urban and rural area in a region, respectively.

The disaggregated urban/rural household consumption (H^{urb} and H^{rur}) in a region can be calculated by multiplying adjusted per capita urban/rural consumption with urban/rural population, estimated as:

$$H^{urb} = M^{urb} \cdot P^{urb} \tag{5.1}$$

$$H^{rur} = M^{rur} \cdot P^{rur} \tag{5.2}$$

After obtaining the disaggregated household consumption of urban and rural areas, we use the consumption structure data from HCSs, that is, the shares of different product categories in the total household consumption for the urban/rural area, to estimate the consumption of product i for urban and rural households ($H_i^{urb^*}$and $H_i^{rur^*}$):

$$H_i^{urb^*} = S_i^{urb} \cdot H^{urb} \tag{6.1}$$

$$H_i^{rur^*} = S_i^{rur} \cdot H^{rur} \tag{6.2}$$

where S_i^{urb} and S_i^{rur} are the consumption share of product i in urban and rural households, respectively.

However, the estimated consumption of product i for urban and rural households could not be directly used for the calculation of urban/rural HGFs, as the sum of urban and rural household consumption of product i might not equal the total household consumption of product i in the MRIO tables due to inconsistency between data sources. Thus, referring to approach of Steen-Olsen et al. (2016) and Wiedenhofer et al. (2016), we split the total household consumption of product i in region r into urban and rural groups by multiplying urban/rural share with finished sector-specific product produced ($H_{i,r}$) as:

$$H_{i,r}^{urb} = \frac{H_{i,r}^{urb^*}}{H_{i,r}^{urb^*} + H_{i,r}^{rur^*}} \cdot H_{i,r}^{urb} \tag{7.1}$$

$$H_{i,r}^{rur} = \frac{H_{i,r}^{rur^*}}{H_{i,r}^{urb^*} + H_{i,r}^{rur^*}} \cdot H_{i,r}^{rur} \tag{7.2}$$

where $H_{i,r}^{urb}$ and $H_{i,r}^{rur}$ are the product i consumed by households in region r which are allocated to the urban and rural groups, respectively.

2.4. Kaya identity

After the disaggregation of household consumption, we estimate the HGFs for urban and rural regions ($E^{urb,\ rur}$):

$$E^{urb,rur} = \sum_r \sum_i C_{i,r} \cdot H_{i,r}^{urb,rur} \tag{8}$$

where $C_{i,\ r}$ is the emissions intensity of consuming a product i in region r, $H_{i,\ r}^{urb,\ rur}$ is the product i consumed by households in region r.

The urban and rural household GHG emissions can be decomposed into emission intensity ($C_{i,r}$), consumption structure ($S_{i,r}$), per capita consumption level (G_r), population size (P_r), urbanization level (U_r) and consumption convergence (R_r):

$$\begin{aligned} E^{urb,rur} &= \sum_r \sum_i C_{i,r} \cdot \frac{H_{i,r}^{urb,rur}}{H_r^{urb,rur}} \cdot \frac{H_r}{P_r} \cdot P_r \cdot \frac{P_r^{urb,rur}}{P_r} \cdot \frac{\frac{H_r^{urb,rur}}{P_r^{urb,rur}}}{\frac{H_r}{P_r}} \\ &= \sum_r \sum_i C_{i,r} \cdot S_{i,r}^{urb,rur} \cdot G_r \cdot P_r \cdot U_r^{urb,rur} \cdot R_r^{urb,rur} \end{aligned} \tag{9}$$

where $E_{i,\ r}^{urb,\ rur}$ is the HGFs in the urban/rural area. $C_{i,\ r}$ is the emissions intensity of consuming a product i in region r. $H_{i,\ r}^{urb,\ rur}$ is the product i consumed by households in region r. $H_r^{urb,\ rur}$ is the total urban/rural household consumption in region r. H_r is the total household consumption in region r. $P_r^{urb,\ rur}$ is the total urban/rural population in region r. P_r is the total population in region r. $S_{i,\ r}^{urb,\ rur}$ is the share of product i in the total urban/rural consumption of region r. G_r is the per capita consumption level in region r. P_r is the total population in region r. U_r is the share of urban/rural population in the total population in region r, which reflecting the urbanization level. $R_r^{urb,\ rur}$ is the ratio difference in per capita consumption between the urban/rural area and the national average level. If the $R_r^{urb,\ rur}$ is 1, the urban/rural per capita consumption equals to the national average level.

2.5. Decomposition analysis

We use the Logarithmic Mean Divisia Index (LMDI) for analyzing emission drivers as it has a relatively sound theoretical foundation, good applicability, and ease of interpretation (Ang, 2005). We carry out the decomposition following Ang (2015) based on the Eq. (8) from the base year *0* to the target year *t*. The aggregate HGFs change $\Delta E^{urb,\ rur}$ can be decomposed into six factors as follows.

$$\begin{aligned} \Delta E^{urb,rur} &= \Delta E_C^{urb,rur} + \Delta E_S^{urb,rur} + \Delta E_G^{urb,rur} + \Delta E_P^{urb,rur} + \Delta E_U^{urb,rur} \\ &\quad + \Delta E_R^{urb,rur} \end{aligned} \tag{10}$$

where

$$\Delta E_C^{urb,rur} = \frac{E_t^{urb,rur} - E_0^{urb,rur}}{\ln E_t^{urb,rur} - \ln E_0^{urb,rur}} \ln\left(\frac{C_t^{urb,rur}}{C_0^{urb,rur}}\right) \tag{11.1}$$

$$\Delta E_S^{urb,rur} = \frac{E_t^{urb,rur} - E_0^{urb,rur}}{\ln E_t^{urb,rur} - \ln E_0^{urb,rur}} \ln\left(\frac{S_t^{urb,rur}}{S_0^{urb,rur}}\right) \tag{11.2}$$

$$\Delta E_G^{urb,rur} = \frac{E_t^{urb,rur} - E_0^{urb,rur}}{\ln E_t^{urb,rur} - \ln E_0^{urb,rur}} \ln\left(\frac{G_t^{urb,rur}}{G_0^{urb,rur}}\right) \tag{11.3}$$

$$\Delta E_P^{urb,rur} = \frac{E_t^{urb,rur} - E_0^{urb,rur}}{\ln E_t^{urb,rur} - \ln E_0^{urb,rur}} \ln\left(\frac{P_t^{urb,rur}}{P_0^{urb,rur}}\right) \tag{11.4}$$

$$\Delta E_U^{urb,rur} = \frac{E_t^{urb,rur} - E_0^{urb,rur}}{\ln E_t^{urb,rur} - \ln E_0^{urb,rur}} \ln\left(\frac{U_t^{urb,rur}}{U_0^{urb,rur}}\right) \tag{11.5}$$

$$\Delta E_R^{urb,rur} = \frac{E_t^{urb,rur} - E_0^{urb,rur}}{\ln E_t^{urb,rur} - \ln E_0^{urb,rur}} \ln\left(\frac{R_t^{urb,rur}}{R_0^{urb,rur}}\right) \tag{11.6}$$

By applying Eqs. (11.1)–(11.6), we can compare a series of factors and discuss their impacts on urban/rural HGFs trends during 2005–2010 and 2010–2015. To estimate the effect of various factors on the total HGFs during 2005–2010 and 2010–2015, we sum the impact of factors on urban and rural HGFs and extend Eqs. (11.1)–(11.6) as:

$$\Delta E_C = \sum_{urb,rur} \Delta E_C^{urb,rur} \tag{12.1}$$

$$\Delta E_S = \sum_{urb,rur} \Delta E_S^{urb,rur} \tag{12.2}$$

$$\Delta E_G = \sum_{urb,rur} \Delta E_G^{urb,rur} \tag{12.3}$$

$$\Delta E_P = \sum_{urb,rur} \Delta E_P^{urb,rur} \tag{12.4}$$

$$\Delta E_U = \sum_{urb,rur} \Delta E_U^{urb,rur} \tag{12.5}$$

$$\Delta E_R = \sum_{urb,rur} \Delta E_R^{urb,rur} \tag{12.6}$$

Urbanization promotes migration from rural to urban areas, which will lead to an increase of urban population and thus ΔE_U^{urb} would induce an increase of urban HGFs. Conversely, people moving from rural areas to urban areas will lead a reduction of rural population, thus ΔE_U^{rur} sees a decrease of rural HGFs. There is a different level of consumption in urban and rural regions over time which results in different emissions. Typically, urban consumption is higher than the national average and rural consumption is lower. If these change over time the net result of this change can result in net emission reductions or increases. That is, convergence between the two areas can also drive changes in emissions on net.

3. Results

We first describe the distribution of HGFs for the six product categories and 16 regions during 2005–2010 and 2010–2015. Then, we decompose total/urban/rural HGF into six factors (emission intensity, consumption structure, consumption convergence, urbanization, population, consumption level). Finally, we present the details underlying the structural transitions in consumption.

3.1. The distribution of household GHG footprints

Total HGFs increased from 19 Gt in 2005 to 19.6 Gt in 2010, increasing further to 20.1 Gt by 2015 (accounting for more than 50% of global total GHGs during 2005–2015) (Fig. 1.a). As urban residents typically consume a greater variety of goods and services than rural residents, urban HGFs contributed 76.9% to total HGFs in 2005, increasing to 77.2% in 2015. Urban HGFs increased by 0.8 yr^{-1} from 2005 to 2010, and 0.4% yr^{-1} between 2010 and 2015. Rural HGFs saw a small decrease between 2005 and 2010 (at −0.1% yr^{-1}), followed by a relatively fast growth between 2010 and 2015 (at 1.0% yr^{-1}), presumably due to an improvement in rural living conditions (Liu et al., 2021). Food and housing, as primary necessities, were the main sources of the total HGFs between 2005 and 2015, responsible for 50% of the total increase. Increasing demand for housing and electrification resulted in an increase in the share of housing in HGFs (from 19.8% in 2005 to 22.6% in 2015). Rural residents with a lower income exhibited a higher share of food in total expenditure than urban residents. However, from 2005 to 2015, the share of food in rural HGFs declined faster than in urban areas, from 33.4% to 30% compared to 23.9% to 22.6% in urban regions. This was largely due to a shift from food towards housing in rural areas. The emission share of housing increased from 18.1% in 2005 to 24.4% in 2015.

Due to high incomes and urbanization, the USA and EU represent the largest emitters at 30.1% and 23.1% of total HGFs in 2005, respectively (Fig. 1.b). They were also the two leading economies in terms of urban HGFs, accounting for 32.2% and 22.7% of the total urban HGFs. China, due to a transition towards consumption-driven economic growth and away from investments one saw a rapid increase to about one-fifth of

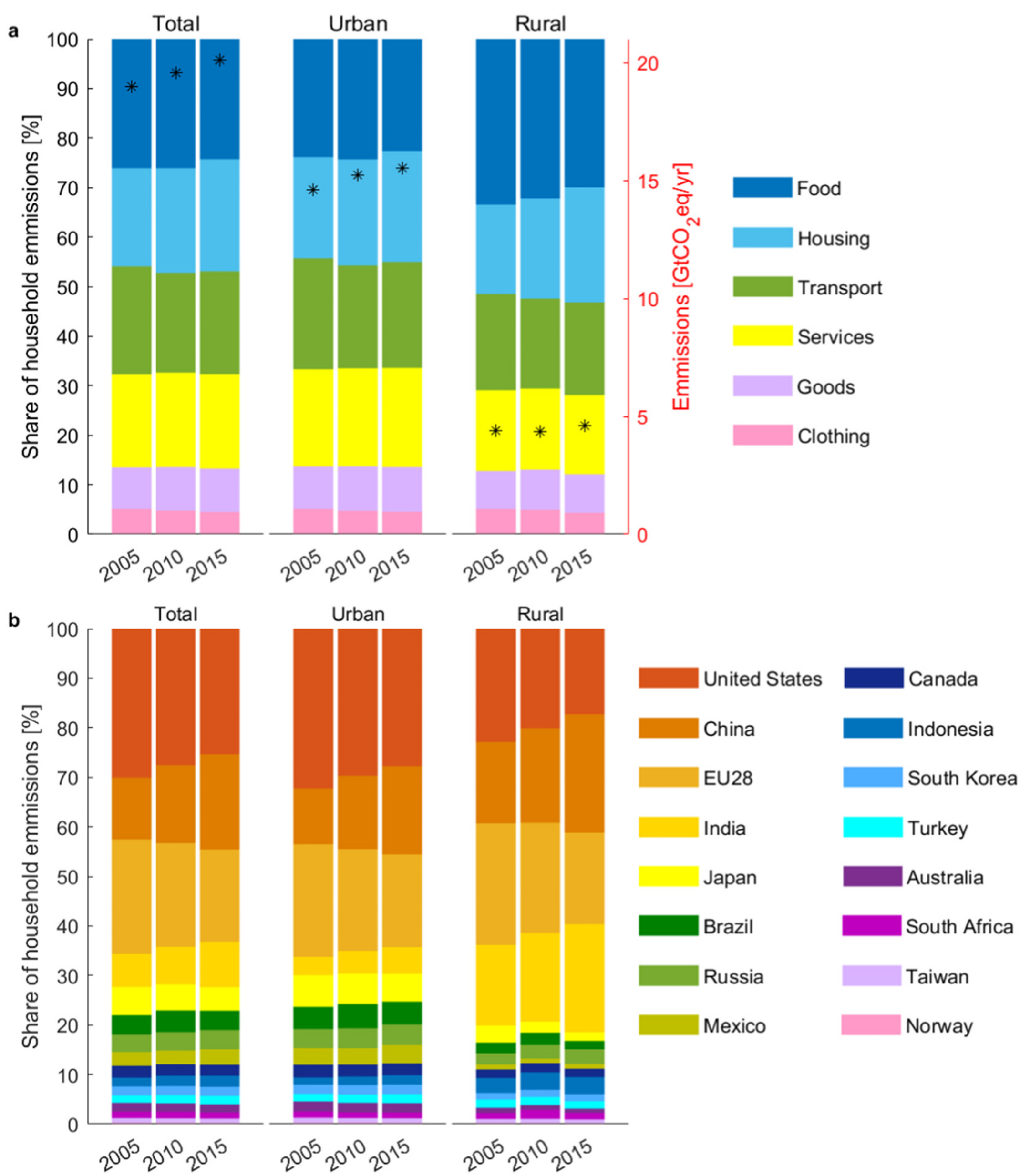

Fig. 1. Distribution of total household GHG footprints from 1995 to 2015. (a) by consumption categories; (b) by regions. (*) indicates the total emissions of 16 regions.

the total by 2015. India also became a new source of growing emissions, accounting for 9.2% of the total by 2015. With fast urbanization, China and India increased their shares of urban HGFs to 17.8% and 5.4% over the ten years, respectively. Income growth in rural areas across these developing nations meant that by 2015, China and India were major contributors to global rural HGFs (at 24% and 21.8% respectively).

For ease of presentation, we divide the 16 regions into two groups based on income per capita. India, Indonesia, China, South Africa, Russia, Mexico, Brazil and Turkey are countries with high levels of economic development and rapid urbanization, identified as emerging regions, other regions are identified as high-income regions with developed economies and high levels of urbanization (Fig. 2).

Due to the difference in consumption patterns between emerging and advanced nations, food was the main component of urban HGFs in emerging regions (53.3%, 47.1% and 65.5% in India, Indonesia and Brazil respectively), while transport accounted for the largest share of urban HGFs in advanced regions (29.2%, 29.3% and 31.3% for Taiwan, the United States and Norway respectively) (Fig. 2a-c). Between 2005 and 2015, the emission share of food in emerging regions decreased from an average of 38.8% in 2005 to an average of 33.2% in 2015. Particularly, several major emerging nations, for example India, Russia, Brazil, experienced a significant decrease, with −7.8%, −11.2% and −10.0%, respectively. However, the emission share of housing in emerging nations increased from an average of 16.5% in 2005 to an average of 18.1% in 2015. The emission share of housing in Russia increased the most significant by 5.4% during 2005–2015. In advanced regions, urban household demand shifted from food and housing towards transport and services. For instance, the share of transport in Canadian total urban HGFs increased from 25.6% to 35.5% between 2005 and 2015. Similarly, the emission share of services in South Korea increased from 26.9% in 2005 to 32.4% in 2015.

In emerging regions, the share of food in total rural HGFs was higher than that in total urban HGFs during 2005–2015 (58%, 58% and 63.1% of rural HGFs in India, Indonesia and Brazil in 2015, respectively) (Fig. 2d–f). Due to the continuous increase of housing and electricity demand, housing surpassed food to become the largest component of rural HGFs in China, accounting for 38.2% of the total rural HGFs in 2015. With this income growth, rural consumption patterns also shift from food to entertainment needs (e.g., transport and services) in advanced regions. For example, in 2015, the share of transport in the rural HGFs in Canada, the United States and Norway increased to 40%, 33.9% and 37.8%, respectively, and the share of services in South Korean rural HGFs climbed from 26% in 2005 to 31.7% in 2015. Thus, we could see an automatic relative decoupling with income rise, due to the reduction of environmentally and energy intensive consumption (Scherer et al., 2019).

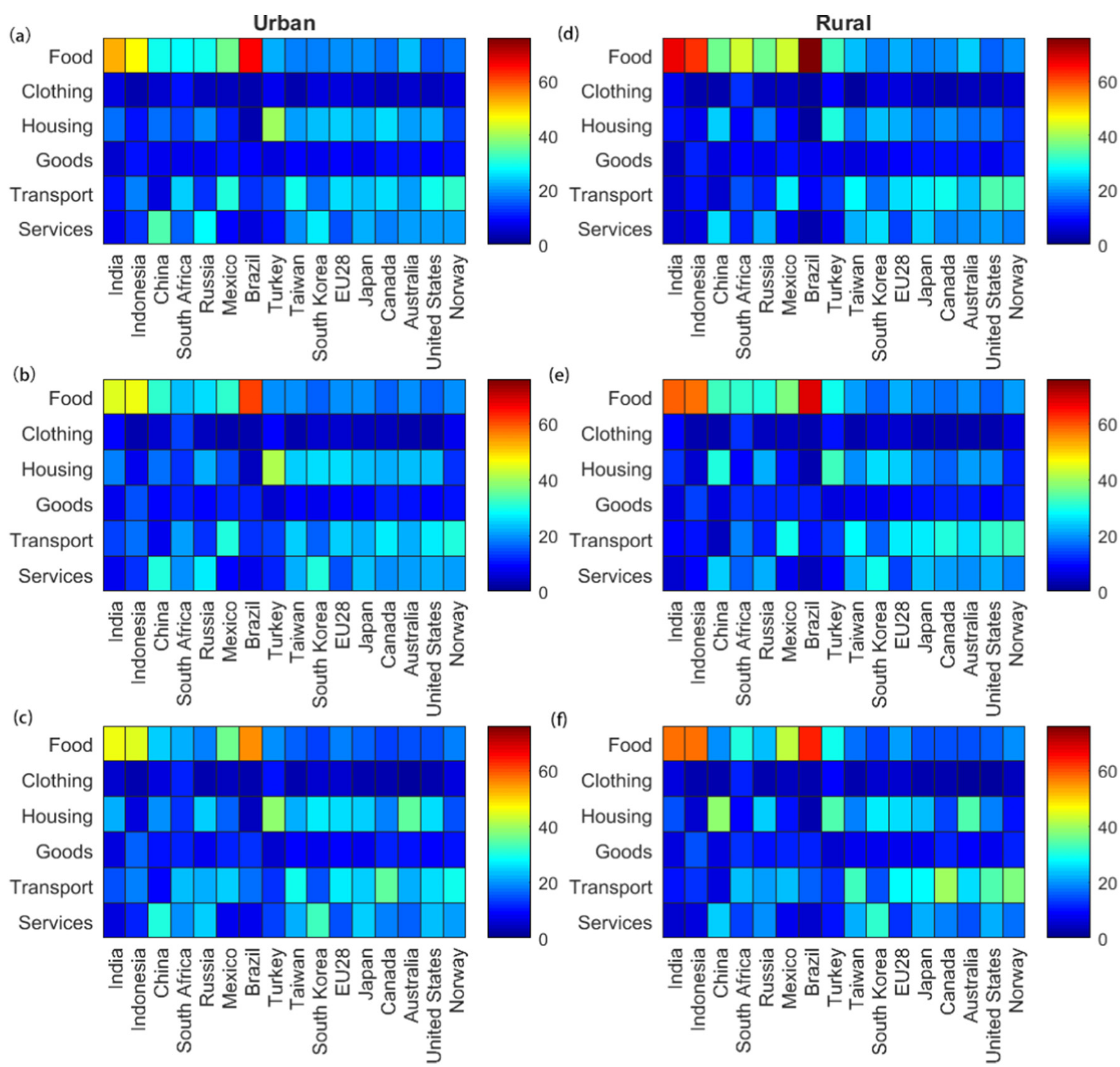

Fig. 2. Household emissions by consumption in 16 regions. (a) 2005 urban HGFs; (b) 2010 urban HGFs; (c) 2015 urban HGFs; (d) 2005 rural HGFs; (e) 2010 rural HGFs (f) 2015 rural HGFs. Note: ordered by regional income per capita. Colors present the emission share of six products.

3.2. Drivers of global household GHG emissions

During 2005–2010, the increase of total emissions was mainly from rapid urban growth in HGFs, which was driven mainly by increasing consumption and population, contributing 9.2%, and 3.7%, respectively (Fig. 3.b). Improving emission intensities drove an 8.6% reduction in urban HGFs. During 2010–2015, slow growth in urban HGFs was due to a strong reduction in emission intensity, resulting in a 15.1% reduction of urban HGFs, offsetting emissions from consumption increases (+14.7%). Urbanization continued to cause an expansion of urban population, which caused a more than 3% increase in urban HGFs during 2005–2015. As urban per capita consumption is higher as the national average level, with the narrow down of this difference, the consumption convergence drove a 1.5% and 2.7% reduction in urban HGFs during 2005–2010 and 2010–2015, respectively. The impact of consumption pattern shifts saw two different patterns. During 2005–2010, the consumption structure saw a shift from food to housing due to building expansion during the urbanization process (Zhang et al., 2019). The change in the share of housing caused a 1.5% increase in urban HGFs. During 2010–2015, urbanization and increased income drove increased transport infrastructure and the increase of private cars (Wiedenhofer et al., 2016), leading to a new consumption structure shift from food towards transportation. The change in transport share saw a 0.8% increase in urban HGFs.

During 2005–2010, the slow reduction in rural HGFs was dominated by emission intensity reductions (−9.1%) (Fig. 3.c). Urbanization drove a shrinking population in rural areas, leading a 6.7% reduction of rural HGFs. Between 2010 and 2015, increasing consumption drove increases in rural HGFs of 21.6%, which was the main driver for rapid rural HGF increases. With the improvement of living conditions and the alleviation of poverty in rural areas, the rural per capita consumption rose towards the average consumption level across nations, pushing rural HGFs upward steadily by 3.9% over the period. In rural areas, consumption structures experienced a more signification shift from food towards housing with the income growth during 2005–2010. The change in the share of food drove a 4.8% reduction of rural HGFs, while the change in the share of housing drove an increase of 2.7%. As villages were provided with expanded access to basic transport, during 2010-2015, the rural consumption structure starts to undergo a shift from food towards transport. The share of transport in the total consumption drove a 2% increase of rural HGFs.

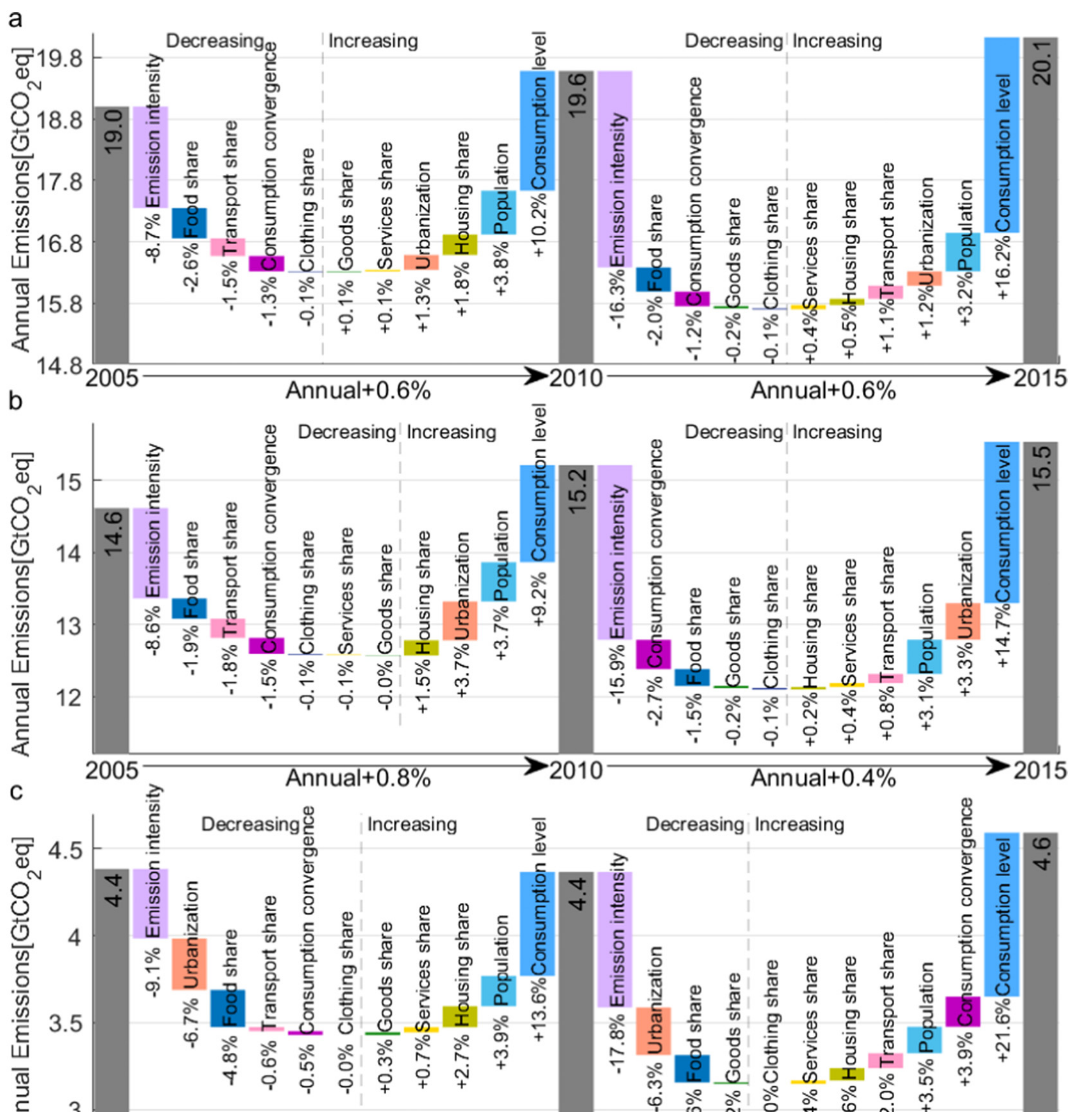

Fig. 3. Contribution of factors to the changes in HGFs. (a) total; (b) urban; (c) rural.

Overall, improving emission intensities offset around 62.1% and 84% of the emission increases caused by consumption and population during 2005–2010 and 2010–2015, respectively (Fig. 3a). Urbanization drove a > 1% increase in total HGFs during 2005–2015. Since the emissions reduction induced by the decrease in the ratio between urban per capita consumption and the average level could be offset the emissions growth induced by the increase in the in the ratio between rural per capita consumption and the average level, the consumption convergence contributed to a more than 1% reduction of total HGFs during 2005–2015. During 2005–2010, as consumption patterns shifted from food to housing, a decrease in the share of food in the total consumption induced a 2% decline in HGFs, and an increase in the share of housing in the total consumption induced a 1.8% growth in HGFs. During 2010–2015, the expansion of transport infrastructure promotes a new consumption pattern shift from food to transport, and an increase in the share of transport in the total consumption induced a 1.1% growth in HGFs.

3.3. Drivers of regional household GHG emissions

Emerging regions, by definition, are experiencing a period of rapid economic development. As such, increasing consumption drove significant increases in HGFs across emerging regions (Fig. 4). Consumption increases drove a 49.7% increase in total HGFs in China during 2010–2015, potentially due to national policies to promote the domestic consumption. Unsurprisingly, due to China's fast urbanization, Chinas urban regions saw faster HGF growth, seeing an increase of 43.4% and 49.3% in urban HGF during 2005–2010 and 2010–2015, respectively. The impact of increasing Indian consumption also induced a 27.3% increase of the total HGFs. Because most of the population in India lives in rural areas and comprises a large market, the impact of consumption level on rural HGFs was large, driving increases in rural HGFs of 34.4% and 45.3% during 2005–2010 and 2010–2015, respectively. Due to the rapid acceleration of migration towards cities, urbanization had a significant impact between 2010 and 2015 on the total HGFs across emerging regions, with the largest impact on China (5.6%) followed by Indonesia (1.7%), India (1.4%) and Mexico (1.3%). Population as a driver of HGFs was largest in Mexico, Turkey and Australia, leading to a 7.6%, 8.1% and 7.2% increase over 2010–2015, respectively.

Improving emission intensities reduced total HGFs across all advanced regions, and was larger than the driving effect of consumption increases, leading to a net decline in the total HGFs in the EU and Japan. This reflects some level of absolute decoupling between

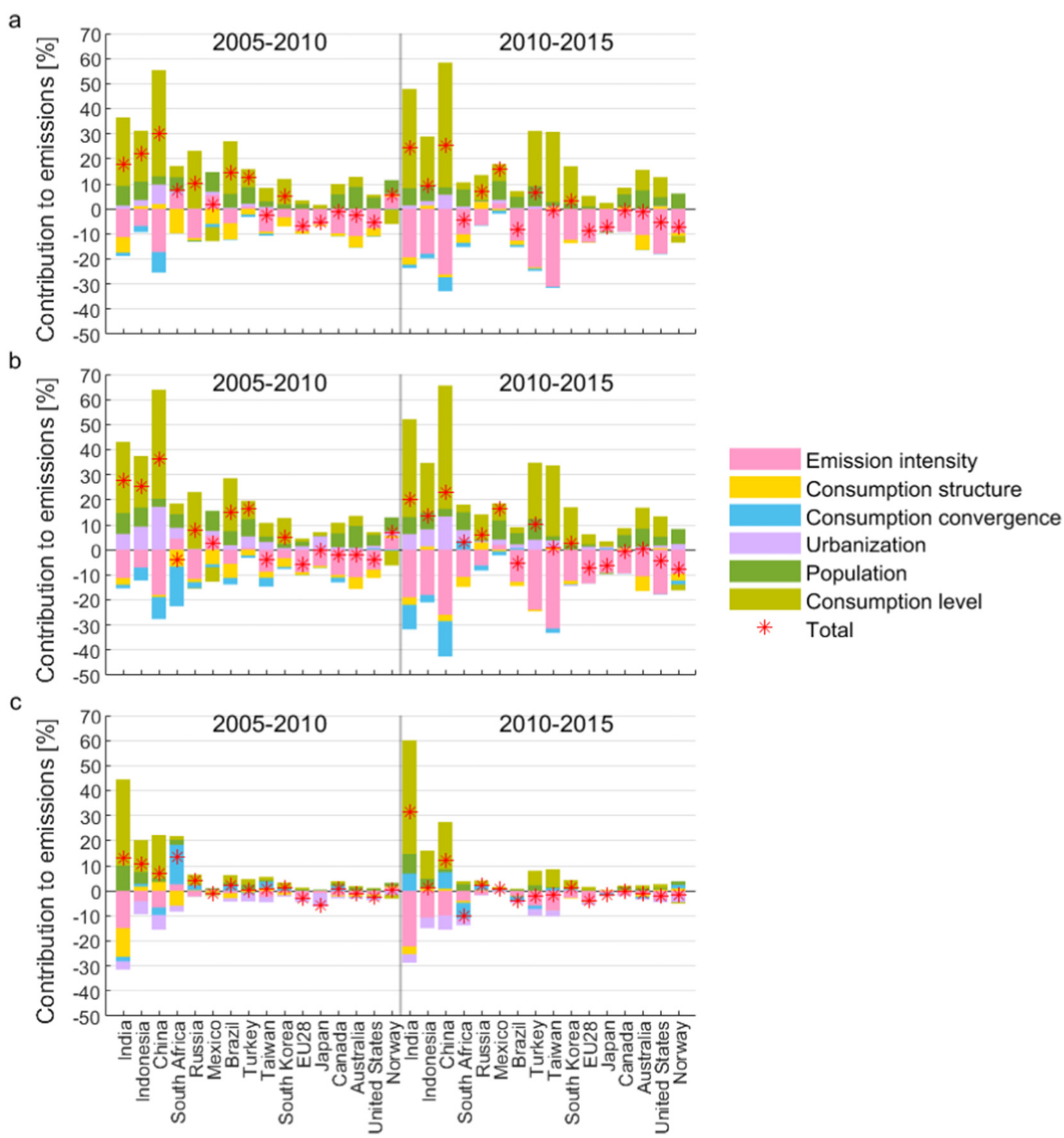

Fig. 4. The contribution of different factors to changes in total HGFs across 16 regions. (a) total; (b) urban; (c) rural. Note: ordered by regional income per capita in 2015. Red stars denote the total emissions changes.

consumption growth and carbon emissions. However, in several emerging regions, emission intensities pushed up the growth of total HGFs, contributing around 5% to the growth of total HGFs in Mexico and South Africa, with the predominant impact on urban HGFs (4.5% for Mexico and 5.6% for South Africa). Consumption convergence was another driver of HGF decreases, with large impacts on the HGFs in emerging regions (e.g., China −5.6%, Indonesia −1.8%, South Africa −1.7%, and India −1.4%). During 2005–2015, emerging regions experienced an important consumption structure shift (a significant reduction of food share in the total consumption budget) resulting in large decreases in total HGFs, with the largest impact in South Africa during 2005–2010 (−9.8%). The decline in rural Indian poverty resulted in a consumption structure transformation in recent decades, the consumption structure induced an 11.5% and 3.2% decrease of rural HGFs during 2005–2010 and 2010–2015, respectively.

3.4. Impacts of consumption structure on regional household GHG emissions

Considering the shift of emission hotspots shown in Fig. 2 (e.g., from food towards housing in emerging regions), we need to consider further details underlying the HGF changes due to changes in consumption structure.

As the share of food in budgets decreased, and other shares increased from 2005 to 2015, this change in food share became the major reason for reducing HGFs in emerging regions, with the largest impact in India during 2005–2010 (12.1%) (Fig. 5). With rapid decreases in the rural budget share of food across emerging regions, the change of food share decreased more HGFs in their rural areas than do urban HGFs. For example, during 2005–2010, the change of food share caused rural HGFs to decline by 18.1% in India, while it only caused urban HGFs to decline by 9.8%.

Increasing population in Mexico and China drove an increase in housing over the period with increases in the need for electricity and heating services with the result that housing as a share of total household expenditure drove a 4.1% and 4.6% increase of HGFs during 2005–2010 for Mexico and Chinn, respectively. This impacted urban areas the most with, for example, 48,966 new houses required in Mexico City each year (SHF, 2016), resulting in a 4.3% increase of urban HGFs during 2005–2010. However, partly due to the promotion of the green mortgage for sustainable housing (CONAVI, GIZ, 2012; National Housing Commission (CONAVI), 2016), during the latter period, 2010–2015, the change in the housing share caused a 1.5% reduction of the total HGFs in Mexico. China also made efforts to reduce housing emissions including the four-year “public-benefit project for

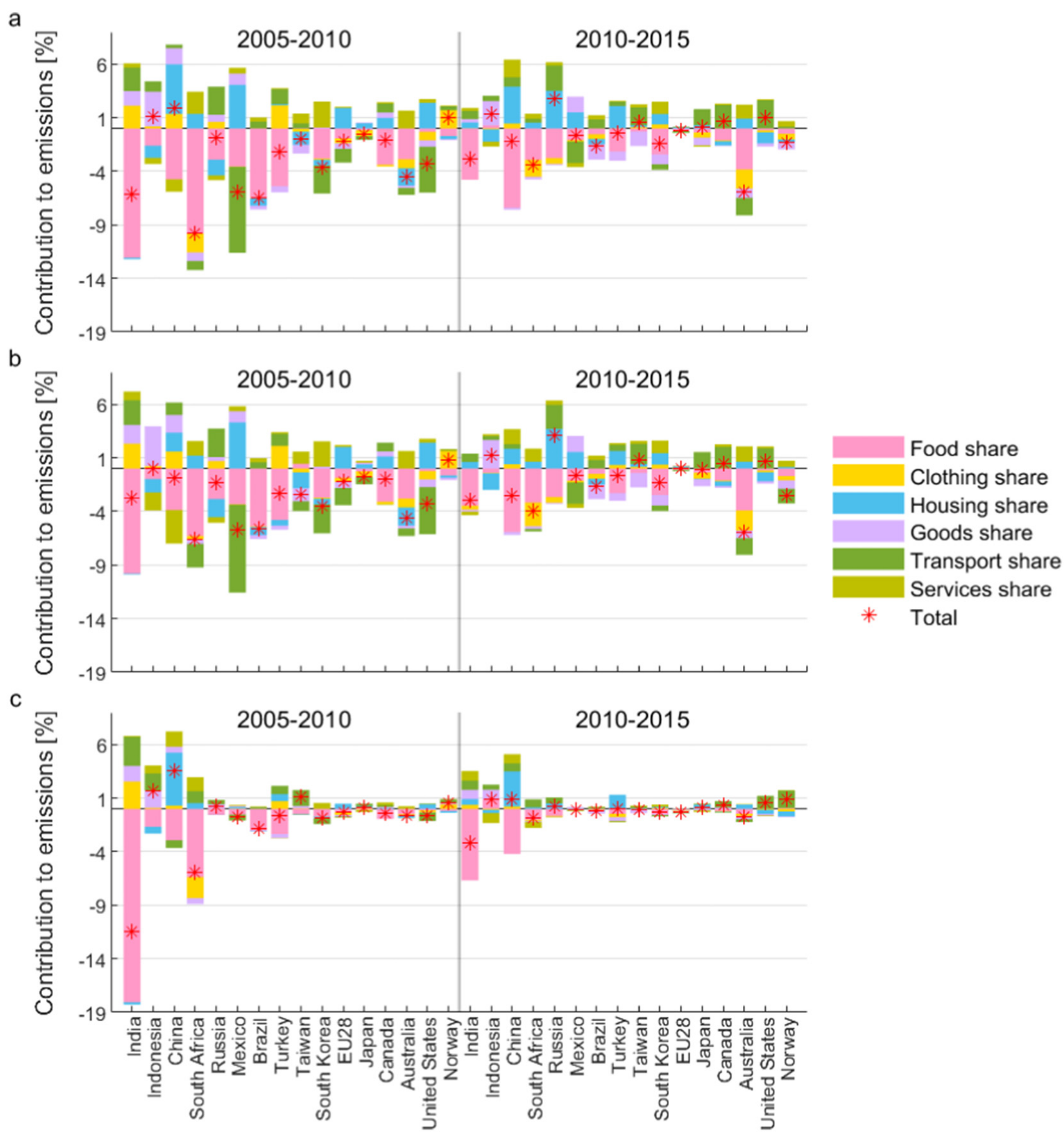

Fig. 5. Contribution of consumption structure to the changes in total HGFs by product categories in 16 regions. (a) total; (b) urban; (c) rural. Note: ordered by regional income per capita in 2015. Red stars denote the total emissions changes.

energy-efficient products" program to increase the penetration of energy-efficient buildings in rural areas after 2009 (Wang et al., 2017; Ma et al., 2019). The impact of this in part explains why the 3.2% increase of rural HGFs in China 2010–2015 was lower than previous period 2005–2010 (at +4.9%). During 2010–2015, the slowly stabilizing economic situation saw a gradually rising demand in Russian housing, driving a 3.7% increase of its urban HGFs.

As the fast income growth in emerging countries simulates greater demand for private vehicles during 2005–2015, the change in the transport share pushed total HGFs in the emerging regions upward significantly (except for Mexico and South Africa). As emerging regions expanded rural transport infrastructure to improve accessibility for remote areas, such as India's rural road scheme (Aggarwal, 2018), which simulated the growth of private transport (e.g. motorbike as noted previously (Schubert et al., 2013, Ishak et al., 2016)), the change of transport share increased rural HGFs more than urban HGFs in India and Indonesia. During 2010–2015, as previous studies indicate, urban residents in several advanced regions (e.g. Canada and Japan) frequently require transportation and their annual travel distances are greater (Ivanova et al., 2018), the driving effects of the change in the transport share on their urban HGFs were larger than rural HGFs.

Due to the issues of accessibility, affordability and convenience of diverse services for urban households, the change in the services share was another driver of urban HGFs growth in all the advanced regions, which reflects a shift of consumption intention from survival-oriented pattern towards to leisure-oriented pattern.

4. Discussion

4.1. A rapid growth of rural household GHG emissions

There was a very large difference in HGFs between urban and rural areas, but this is narrowing over time with an estimated annual growth rate of rural HGFs (at 1% yr^{-1}) larger than that of urban HGFs (at 0.4% yr^{-1}). These changes are mainly because China and India have been making efforts to narrow rural-urban disparities (Hubacek et al., 2017). For example, India carried out various types of transfer payments aimed at rural population (e.g., unemployment compensation, soft loans, and concessions to senior citizens) (Alik-Lagrange and Ravallion, 2018). Since 2004, China has replaced its centuries-old policy of taxing agriculture with a new policy aimed at subsidizing agriculture and stimulating rural income (Lopez and Falcis, 2017). Moreover, the expansion of infrastructure in urban areas, such as heating facilities, leads to more efficient energy use. However, compared to urban households, rural households are more likely to consume coal and LPG, but are less likely to use natural gas (Zou and Luo, 2019; Harrington et al., 2020). Thus, an expansion of electricity access in the rural area leads to a rapid increase of rural HGFs, creating a convergence between the rural and urban HGFs. For example, Wang and Jiang (2017) indicated that the modern and clean energy such as electricity and natural gas are not widely available across rural China, with natural gas only accounting for 4.75% of the households. Yadav et al. (2018) indicated that 400 million rural people have no access to electricity in India, and they mainly rely on coal for cooking.

4.2. A comparison with other studies about urbanization

Internal migration and spatial connections of rural and urban areas has been changed by urbanization deeply. We found that the rapid rural to urban migration in many nations has brought a more than 1% increase of HGFs. Thus, identifying the impact of urbanization across different income-level regions could offer a reference for the national strategies for urbanization and GHGs mitigation, especially for emerging nations aiming to develop a low-carbon future (Peters et al., 2007). We found that the urbanization induced the increase of HGFs across emerging nations. This finding is consistent with previous studies indicating that urbanization increases CO_2 emissions in emerging economies (Martínez-Zarzoso and Maruotti, 2011a; Sadorsky, 2014; Zhang et al., 2017). Rafiq et al. (2016) and Liu et al., (2017) found that urbanization resulted in a small increase of emissions in emerging economies. Wu et al. (2017) and Wang et al. (2018) also found the driving impact of urbanization on the growth of emissions in China and India, respectively. Further urbanization in emerging nations increased HGFs, supporting the urban environmental transition theory that argues that the infrastructure development induced by urbanization is the key contributor to increased emissions in emerging regions (Bakirtas and Akpolat, 2018; Ahmad et al., 2019). Wang et al. (2019) and Song et al. (2018) showed that urbanization and associated income and lifestyle changes had important driving impacts on the growth of CO_2 emissions. However, our results were not supported by Al-mulali et al. (2013), whose findings showed that that urbanization can reduce the emissions in the Middle East and North African (MENA) countries. This is because Al-mulali et al. (2013) focused on MENA countries, which is different from our sample, leading to different results. Since urbanization is projected to increase, this pattern will influence long-term emissions (Mestl and Eskeland, 2009; Li et al., 2019b; Bai et al., 2018). This means that it will be extremely challenging to reduce urbanization-led emissions in emerging economies (e.g., China, India and Mexico) via slowing down the speed of urbanization (Jiang et al., 2019). The major solution would be an improvement in the quality of urbanization. Our findings may provide a baseline for other developing countries in different regions that will see a large amount of urbanization in the coming years.

4.3. Policy implications for shifts in emission patterns

Our data and analysis provide an overall picture to help policymakers understand how the emissions patterns change with income in urban and rural areas. We found that housing has been a prime driver of increasing rural HGFs especially in emerging nations (e.g., China, India and Turkey). This finding is consistent with the continued growth of reconstruction or expansion of housing and grid-based electrification in the rural area across emerging nations during the study period (Zhang et al., 2015; Palit and Bandyopadhyay, 2016). Therefore, a transformation towards renewably generated electricity could provide a large benefit for rural HGF reductions. Another possible solution is to replace energy-intensive building materials in the rural area by recycled materials as a transitional alternative.

We also found that the emission share of transportation in the urban area increased with an ongoing consumption transition from food to transportation, mainly due to urbanization. Since population migration will increase the demand for transportation directly, it is impractical to limit the growth of transportation consumption, particularly in the emerging regions with a rapid urbanization (Li et al., 2019a; Wang et al., 2019; Song et al., 2019). Therefore, providing incentives to car consumers to use more efficient vehicles or shift transport modes is vital. We could observe that the emission intensities of transport in Japan and the EU were lower than those of Russia and Turkey (Fig.S1) since Japan and the EU implemented vehicle replacement schemes to promote the substitution of old vehicles with new fuel-efficient vehicles (European Automobile Manufacturers' Association, 2012; Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2012). Thus, the vehicle replacement schemes in Japan and EU are a good example of HGFs reduction possibilities when emerging regions like India, China and Brazil continue to mimic consumption structure transition towards transport.

4.4. Limitations

Due to data limitations, our study only analyzes 6 consumption categories with urban-rural divisions. This limits this research capacity to present HGFs between different regions at a more disaggregated level.

Future researchers can expand further household consumption data to better explore driving factors of HGFs at the very detailed income group level. Moreover, the lack of household consumption data is a major shortcoming in this study. As the household survey data are not available for all the nations/regions, we have to make an assumption that those nations/regions with no household consumption data have similar consumption patterns with the neighboring year or neighboring regions, which refers to the assumption from Zhao et al. (2019). Moreover, for Brazil (2005), India (2015) and Turkey (2015) without consumption data in neighboring year/regions, we have to follow World Bank recommendations (The World Bank, 2012) and use a linearly interpolation method to obtain the consumption data. Although this might lead to the error for estimation of HGFs, it is still reasonable due to limited data. This is because the consumption patterns are relatively stable in a short period and neighboring nations always have similar consumption patterns due to similar economic levels, culture, and geographic location. In addition, household survey data did not provide specific consumption patterns of domestic and imported products for urban and rural groups, such that we did not use detailed information for a separate disaggregation of household consumption for domestic products and imported products. Finally, we only focus on 16 main regions that are responsible for 80% of global HGFs due to data limitations. Since the urbanization process in emerging regions is rapid, and the rest of world includes many emerging regions (e.g., Cambodia, Thailand and Egypt), our results might underestimate the driving impact of urbanization.

5. Conclusions

Our study shows the important contribution of urban HGFs to total emissions but highlights the fast growth of rural HGFs during 2010–2015 (at 1% yr^{-1}). These findings support a convergent trend of HGFs between urban and rural areas. Moreover, a regional comparison for the distribution of HGFs shows that urban HGFs were concentrated in advanced regions (27.8% in the USA and 18.7% in the EU in 2015) due to their large consumption of transport and services, while the rural HGFs were concentrated in emerging regions (24% in China and 21.8% in India in 2015). Finally, the analysis of driving factors indicates the strong need to reduce emission intensity in the face of the large driving impact from consumption and population growth, as well as urbanization. Specifically, we highlight the importance of the declines in the emission intensities of housing in the rural area and transport in the urban area, considering a consumption transition from food towards housing and transport. Also, we strongly indicate that the increase of HGFs due to the urbanization process was mainly due to the large population migration from rural to urban areas in emerging regions. This contributes to a better understanding of the relationship between urbanization and HGFs from a global perspective.

CRediT authorship contribution statement

Rong Yuan: Conceptualization, Methodology, Writing - Original draft preparation. **João F.D. Rodrigues:** Methodology, Software. **Juan Wang:** Formal analysis, Investigation. **Arnold Tukker:** Supervision. **Paul Behrens:** Writing - Reviewing and Editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150695.

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