Urban Climate Change Mitigation in Europe: Looking at and beyond the Role of Population Density

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Abstract: As climate change mitigation becomes pervasive on all spatial scales, mitigation options related to urban spatial planning and behavioral change become increasingly important. Because transport energy consumption seems to scale inversely with population density, increased attention focuses on the role of urban form. This study specifically analyzes the importance of population density for the reduction of urban greenhouse gas emissions in Europe. For this, drivers of both carbon dioxide (CO_2) emissions from transport (for 134 cities) and total urban greenhouse gas emissions (CO_2eq emissions) of 62 cities across Europe are investigated. Results indicate that population density is not, per se, a strong determinant of greenhouse gas emissions in European cities. Crucially, the spatial scale of the analysis matters and national influences modulate CO_2eq emissions in the analyzed urban areas. Results show that greenhouse gas emissions of European urbanites increase significantly with decreasing household sizes and increasing personal wealth. Although the results are bound by data quality, it is assumed that the relative similarity of European cities is also leading to a lesser degree of importance of population density with respect to climate change mitigation. The results further encourage more thorough analyses of the role of household size and personal wealth for effective mitigation of climate change, additional spatially explicit econometric studies, and detailed, city-specific causal models of urban areas. **DOI: 10.1061/(ASCE)UP.1943-5444.0000165.** *© 2013 American Society of Civil Engineers.*

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Introduction

Although climate change has become a key issue of global policymaking (European Network of Construction Companies for Research and Development 2011; Smit and Pilifosova 2001), carbon dioxide (CO_2) concentrations in the atmosphere are continuing to increase (International Energy Agency 2011). If the worst impacts of climate change are to be averted, urgent action is needed to reduce CO_2 emissions and to create more climate-friendly and sustainable developments.

In this context, cities have been identified as crucial components (Hoornweg et al. 2011; Norman et al. 2006; Rickwood et al. 2008; Russo and Comi 2011; United Nations Human Settlement Programme 2011; Zhao et al. 2011) because they are home to more than 50% of the human population; thus, they are the major consumers of energy and natural resources. However, their actual contribution to climate change is less clear (Romero Lankao and Dodman 2011). In this respect, the consumption of transportation fuel is especially seen as not only an important determinant of greenhouse gas (GHG) emissions, but also as "...the greatest source of uncertainty in the total [urban GHG] inventory due to the [varying] estimation procedures involved" (Kennedy et al. 2009a, p. 4).

With climate change mitigation becoming a prevalent issue on all spatial scales, mitigation options related to urban spatial planning and behavioral change are becoming increasingly important. Cities "[. . . have] the unique ability to respond to [. . .] climate change at a local, more visceral level . . . " (Hoornweg et al. 2011, p. 2). Thus, they need to become laboratories for effective climate change mitigation actions. Therefore, currently existing climate change mitigation policies seek further empirical foundation and coherent insights into the primary determinants of urban GHG emissions.

In this respect, urban form related drivers (such as urban sprawl) and socioeconomic variables (such as income) are of paramount importance (European Environment Agency 2006; Feng and Li 2012; Huang et al. 2007; Schwarz 2010; Zhang et al. 2010). An important study was provided by Newman and Kenworthy in 1989 (NK) when they identified an inverse proportional relationship between population density and transport energy consumption for 32 primary global cities (Newman and Kenworthy 1989). Based on these findings, they drafted policy recommendations for realizing fuel saving potentials and reducing transport GHG emissions by changing urban form parameters (e.g., increasing population density). These recommendations have been broadly considered in international policy-making (Wegener 1996) and have been widely promoted for advantageous urban planning (Barrett 1996; Black 1996; Breheny 1995; Cervero 1988; Creutzig et al. 2012a; Mindali et al. 2004). Recent studies substantiated the NK correlation, especially within the U.S., showing a comparable influence of population density not only on transport GHG emissions, but also on housing: denser housing relates to less energy consumption by heating (Ewing and Cervero 2010; Ewing et al. 2007).

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However, there are also studies that question the causation implied by the NK's research, because they were not able to reproduce the NK conclusions by applying other statistical methods (e.g., the multivariate "co-plot" approach) or newer data (Mindali et al. 2004). Conclusions range from a rejection of population density as the primary driver of transport GHG emissions (Mindali et al. 2004) to the deduction that population density is an important determinant of urban GHG emissions, but not the only one (Rickwood et al. 2008).

In support of the preceding statement (Rickwood et al. 2008), Kennedy et al. (KEN) analyzed the GHG emissions of 10 global cities (Kennedy et al. 2009a, b). They identified population density as a strong determinant of transport GHG emissions, but also concluded that there are further drivers that are equally important for limiting urban GHG emissions. They found strong impacts of the temperature regime [in terms of heating degree days (HDD)] and income per capita (for selected data) on the amount of fuel used for heating and industrial purposes.

Motivated by NK's finding for global cities and by KEN's general conclusion that urban GHG emissions are also determined by other important drivers, both assumptions are reinvestigated in this study for European cities. Therefore, the transport GHG emissions of European cities are analyzed, focusing on different spatial scales. This aims to reconsider NK's inverse proportional relationship between population density and transport GHG emissions. Second, the view is broadened and other socioeconomic drivers of aggregate GHG emissions are searched for in 62 European cities.

In the end, it is concluded that the spatial scale of analysis matters: whereas NK found a strong impact of population density on the global scale, a similar finding cannot be confirmed for the European (continental) scale. However, this effect is identified on a national level. Furthermore, it is concluded that the amount of per capita GHG emissions is significantly determined by the amount of people living in one household (household size) and by the personal wealth of European urbanites. Again, strength and statistical relationship (inverse proportional or linear) depend on the scale of the analysis.

Data and Methodology

Data

To reinvestigate NK's finding regarding transport CO_2 emissions two different data sources were used. First, NK's 1996 published data for global cities were reanalized (Kenworthy and Laube 1996). This data set was available in the "Millennium Cities Database" (Kenworthy et al. 2001) and consisted of 88 international cities (the original publication from 1989 contained 32 global urban areas). Second, a map was created of global ground transportation CO_2 emissions (base year: 2005) by using the Emissions Database for Global Atmospheric Research, or EDGAR [European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL) 2009]. More precisely, the EDGAR data set "v41 1A3b_c_e" was used, which contained emissions from road, rail, and other ground transportation modes with a spatial resolution of $0.1° \times 0.1°$. Finally, city vector data were used from Eurostat's geographical information system, "GISCO" (Eurostat 2011a), to create CO_2 emission subsamples for 302 European cities (using the administrative boundaries); thus, median CO_2 data were produced for transport in European cities.

Comparing GHG inventories of different cities is often difficult because, in many cases, there is no common definition of which emissions to include (Hoornweg et al. 2011). Hence, the authors

Table 1. List of 62 Analyzed European Cities and Their Annual Total Urban GHG Emissions

City	Country	CO_2eq (t/capita)
Aberdeen (m)	U.K.	7.7
Augsburg (m)	Germany	9.69
Basel (m)	Switzerland	5.2
Belfast (m)	U.K.	7.7
Birmingham (mi)	U.K.	5.4
Bochum (m)	Germany	8.25
Bologna (m)	Italy	11.1
Bradford (l)	U.K.	5.2
Bremen (l)	Germany	17.06
Bristol (m)	U.K.	4.7
Brno (m)	Czech Republic	6.43
Cambridge (m)	U.K.	5.8
Cardiff (m)	U.K.	6.3
Cologne (l)	Germany	10.09
Coventry (m)	U.K.	5.2
Derry (m)	U.K.	6.9
Dortmund (l)	Germany	7.03
Edinburgh (m)	U.K.	6.1
Essen (l)	Germany	10.75
Exeter (m)	U.K.	4.8
Frankfurt (Main) (l)	Germany	12.79
Freiburg (Breisgau) (m)	Germany	7.97
Geneva (m)	Switzerland	7.8
Glasgow (l)	U.K.	8.8
Gravesham (s)	U.K.	6.5
Hamburg (mi)	Germany	9.12
Helsinki (l)	Finland	6.01
Joenkoeping (m)	Sweden	3.19
Kingston upon Hull (m)	U.K.	5.95
Leeds (l)	U.K.	5.5
Leicester (m)	U.K.	5.8
Lincoln (s)	U.K.	5.1
Liverpool (m)	U.K.	5.6
London (mi)	U.K.	6.02
Mainz (m)	Germany	8.5
Manchester (m)	U.K.	5.6
Naples (l)	Italy	4
Newcastle (upon-Tyne) (m)	U.K.	6.1
Nottingham (m)	U.K.	5.4
Nuernberg (l)	Germany	7.4
Oerebro (m)	Sweden	4.6
Oulu (m)	Finland	13.6
Porto (m)	Portugal	7.3
Portsmouth (m)	U.K.	5.4
Prague (mi)	Czech Republic	7.85
Sheffield (l)	U.K.	5.7
Stevenage (s)	U.K.	6.5
Stockholm (l)	Sweden	3.62
Stoke on trent (m)	U.K.	5.8
Strasbourg (m)	France	6.6
Stuttgart (l)	Germany	8.42
Torino (l)	Italy	9.7
Venezia (m)	Italy	10
Vienna (mi)	Austria	5.19
Warszawa (mi)	Poland	6.29
Wiesbaden (m)	Germany	11.5
Winterthur (s)	Switzerland	4.42
Wirral (m)	U.K.	5
Wolverhampton (m)	U.K.	5.4
Worcester (s)	U.K.	5.3
Wrexham (m)	U.K.	10
Zurich (m)	Switzerland	3.7

Note: Includes Scope 2 and upstream emissions for electricity generation) and city size classes of small (s), medium (m), large (l), and million (mi).

created their own database to allow a sound comparison of the GHG emissions of 62 European cities (a list of all cities under analysis is provided in Table 1). In this paper, a "city" refers to the administrative area of a city, not to the entire urban area or the larger urban zone. Data came from inter alia AEA's technical report written for the Department of Energy and Climate Change, "Local and Regional Carbon Dioxide Emission Estimates for 2005–2009 for the U.K." (Webb et al. 2011), and directly from city commissioners, who primarily used ECOSPEED's online software, *ECO Region*, for calculating their city's GHG emissions from the final energy consumption. Thus, emissions from electricity production, heating, and cooling processes, and transport were considered.

Scope 2 carbon dioxide equivalent (CO_2eq) emissions were used, which made it possible to include emissions from electricity generation, regardless of the specific location of their production (Bhatia and Ranganathan 2004). Additionally, respective upstream emissions have been included and data were adjusted for seasonal variations to account for cities' different climatic conditions. This type of GHG emission data can be regarded as more realistic than simple CO_2 data (Hoornweg et al. 2011; Kennedy et al. 2009b), and the presented data collection can be regarded as one of the most comprehensive data sets of this type for European cities.

In general, the obtained GHG data appeared consistent and only emission data for the German city of Bremen appeared to be noticeably higher than emissions from other cities. However, an in-depth analysis of the underlying GHG inventory did not reveal any anomalies (e.g., specific industrial functions of the city). Hence, there was no reason to exclude Bremen from further analyses.

For the investigation of NK's observation, population density raster data were used from the project "Gridded Population of the World (v3)" (GPW) by the Socioeconomic Data and Applications Center (SEDAC) (Balk et al. 2006). SEDAC uses administrative boundaries or statistical reporting units to grid information from census data. The data set has a spatial resolution of 2.5 × 2.5°; however, the level of detail is constrained by the availability of population data, which may vary substantially across countries. Therefore, only 134 European cities from France, Hungary, Italy, Poland, Portugal, Spain, and the Czech Republic were included in the subsequent analysis to ensure high data quality.

Eurostat's city vector data were used to select the population density data for the respective cities and to aggregate population density and CO_2 emissions within a bounded urban area.

Population density data for the analysis of further GHG determining variables were calculated from city size and census data, both taken from Eurostat's databases (Eurostat 2011b). Data were available for 62 European cities, which were assessed between 2007 and 2009.

For the investigation of further GHG emission drivers, variables were also included for household size [number of people living in one household (PPH)], temperature regime (HDD and cooling degree days), population development (population change over the last five years), personal wealth [purchasing power standard (PPS)], and development of personal wealth (annual changes in PPS from 1999 to 2009). Personal wealth is expected to be especially important because it is an indicator for the lifestyle habits of citizens (Hoornweg et al. 2011). In this regard, PPS was used instead of information on the gross domestic product (GDP) because considering PPS instead of GDP helps to avoid concerns arising from varying national costs of living or differing national economic powers (Eurostat 2011b). More detailed information about the specific socioeconomic variables is included in Table 2.

Methodology

To statistically reinvestigate NK's relationship, data were log-log-transformed, transforming NK's inverse proportional correlation (power law with exponent α) into a straight line (with slope α) in a double logarithmic plot. Thus, linear regression could be used to estimate the slope of the relationship, which facilitated further econometric analyses.

The statistical software *MATLAB* was used to process the EDGAR database and the geospatial population density data. The GPW data were downscaled to the EDGAR data resolution, and thus, allowed for the calculation of median values of population density and transport CO_2 emissions within each urban area.

Investigating further important drivers of urban GHG emissions and also reproducing KEN's analyses required simple and multiple statistical analyses and a model-based clustering approach (*R*: Mclust 4.0), which tested different clustering possibilities (Fraley and Raftery 2007). All analyses were conducted by using the open source statistical software package *R*.

Table 2. List of Further Variables, Used for the Analysis of Annual Total Urban GHG Emissions (data from Eurostat 2011b and BizEE Software 2011)

Variable	Data characteristics	*n*	Date of assessment
Population density (person/km^2)	Minimum: 84.06 (Jönköping) Maximum: 24821.95 (Exeter) Average: 3,568.59	62	2007–2009
Personal wealth in terms of Purchasing Power Standard (PPS)	Minimum: 16,000 (Naples) Maximum: 76,200 [Frankfurt (Main)] Average: 33,264.79	58	2007–2009
Heating/cooling degree days	Available for baseline temperatures: 12.5–18.5°C	62	Calculated for the last 36 months
Household size (person/ household)	Minimum: 1.79 (Zurich) Maximum: 2.77 (Derry) Average: 2.14	54	2003–2006 (mostly)
Population change (annual population growth, %)	Minimum: −2.48 (Porto) Maximum: 1.91 (Cambridge) Average: 0.55	56	2007–2009
Income change (PPS change, %)	Minimum: 0 (Bologna; Mainz) Maximum: 6 (Warszawa) Average: 3	58	1999–2009

Note: Population density is calculated from city size and population size.

To examine the significance of the investigated parameters and the quality of the constructed correlations, the statistical measures r^2 (informing about the quality of an influence) and p-value were used, showing the significance of a parameter's influence (Backhaus et al. 2010; Crawley 2013). Further specifics about the conducted statistical analyses are directly provided in the results.

Results

Controlling GHG Emissions: The Importance of Population Density

The NK study reported that transport GHG emissions (in the form of passenger car usage) and population density are inversely related. This finding was first published in 1989 for 32 global cities (Newman and Kenworthy 1989) and again in 1996 for 88 global cities (Kenworthy and Laube 1996). In both publications, cities are presented in clusters according to their host continents. These clusters follow NK's inverse proportional trend.

This study investigated whether NK's finding is also valid within continents. Hence, Fig. 1 presents their data from 1996, but the data are decomposed into the different continental clusters. It is obvious that within all continents (except for North America), the correlation found between population density and transport GHG emissions is generally weaker than for the global scale.

More precisely, both the strength of the correlation between population density and passenger car usage (power law exponent α) and the quality of the relationship (r^2, presenting the suitability of the constructed trend; p-value, informing about its significance) are much weaker for Europe and South America. For Asia, the negative correlation between population density and passenger car use is only weakly significant.

Population density seems to be less influential on the amount of passenger car usage on the continental level than on the global scale for NK's 88 cities. To investigate this finding in more detail, transport CO_2 emission data for 134 European urban areas from 2005 were analyzed. Fig. 2(a) shows that it is not possible, despite a larger data set, to reconstruct NK's findings for European cities. To verify whether this is similar on further scales, the data were disaggregated to conduct statistical analyses on the national level; Figs. 2(b and c) show exemplary results for France and Spain (countries chosen because of high data quantity). As already anticipated in Fig. 2(a), both cases show that the correlation between population density and transport CO_2 emissions again becomes more obvious (stronger α and r^2 values) on the national level.

When additionally reinvestigating KEN's findings (an inverse proportional relationship between a city's total GHG emissions and its population density for 10 global cities) by analyzing total urban GHG emissions for 62 European cities, only weak statistical results were obtained. Thus, a similar, statistically significant relationship could not be found for the European cities under analysis (Fig. 3).

As a summary, it can be stated that although NK's observation is statistically reliable on a global scale, it is less significant within continents. Population density cannot be identified as a dominant driver for urban GHG emissions for European cities (neither for transportation GHG emissions, nor for total urban GHG emissions). However, respective correlations were stronger on the national level.

Controlling GHG Emissions: Investigating Further Drivers

It may not be possible to fully describe GHG emissions in European cities by only considering population density. Therefore, the authors searched for other, possibly even more important, determinants of urban GHG emissions. Because KEN performed similar analyses for 10 global cities, the findings of the study were also reinvestigated at the European level.

Identified GHG Drivers

To investigate the variables that mostly determine GHG emissions in European cities, various simple regression models were developed that allowed for the investigation of possible relationships between the different variables and CO_2eq emissions. Therefore, data were additionally included in the analyses for household size, population development, personal wealth, development of personal wealth, and temperature regime (cooling degree days). It was found that household size and personal wealth are both highly influential on the amount of GHG emitted by each inhabitant.

Fig. 4 shows that GHG emissions are negatively correlated to household size ($r^2 = 0.21$; p-value $=< 0.01$; $\alpha = -5.34$). In this respect, German cities are mostly characterized by small household sizes ($\emptyset = 1.91$ PPH in these data) and comparably high GHG emissions per capita ($\emptyset = 9.89$ t/person in these data). In contrast, most U.K. cities are among those with the biggest household sizes and the lowest amount of CO_2eq emissions per capita ($\emptyset = 2.32$ PPH; 6.04 t/person, respectively).

Slightly diverging from this trend are cities from Austria, Switzerland, Finland, and Sweden. They are mostly placed underneath the trend line, which means that citizens are predominantly living in medium-sized households (~2 PPH) and emit a comparably smaller amount of GHG emissions per person.

A second finding suggests that the personal wealth of a European urbanite also determines its amount of total CO_2eq emissions. This effect is even stronger than KEN found for global cities (Kennedy et al. 2009b). Thus, Fig. 5 shows a significant positive linear relationship between GHG emissions and personal income per capita ($r^2 = 0.18$; p-value $=< 0.01$).

In detail, results indicate that U.K. citizens have comparatively low PPS and low GHG emissions per capita, whereas German citizens are among the richest city dwellers in the analysis. They also emit the highest amount of CO_2eq emissions per person. On average, citizens in German cities are 32% richer than citizens in U.K. cities, but they also emit 39% more CO_2eq. Generally, an increase in purchasing power of 11,000 PPS units results in one additional ton of GHG emissions per citizens per year in the European cities under analysis.

KEN also found a strong influence of the temperature regime (HDD) of cities on their GHG emissions from heating and industrial processes. Because of data constraints (city commissioners corrected data beforehand for seasonal variations), this trend could not be reproduced for European cities.

Important Variable Combinations

Sources of GHG are various; hence, defining determinants of CO_2eq emissions is a complex task and it may be possible that combinations of socioeconomic variables more adequately describe GHG emissions than single drivers (Hoornweg et al. 2011). Therefore, multiple regression models were also computed to investigate possible combinations of socioeconomic variables that may jointly influence a person's GHG emissions in European cities.

It was found that, if all socioeconomic variables were included in a multiple regression model, they indicated a significant influence of household size (inversely proportional) and an importance

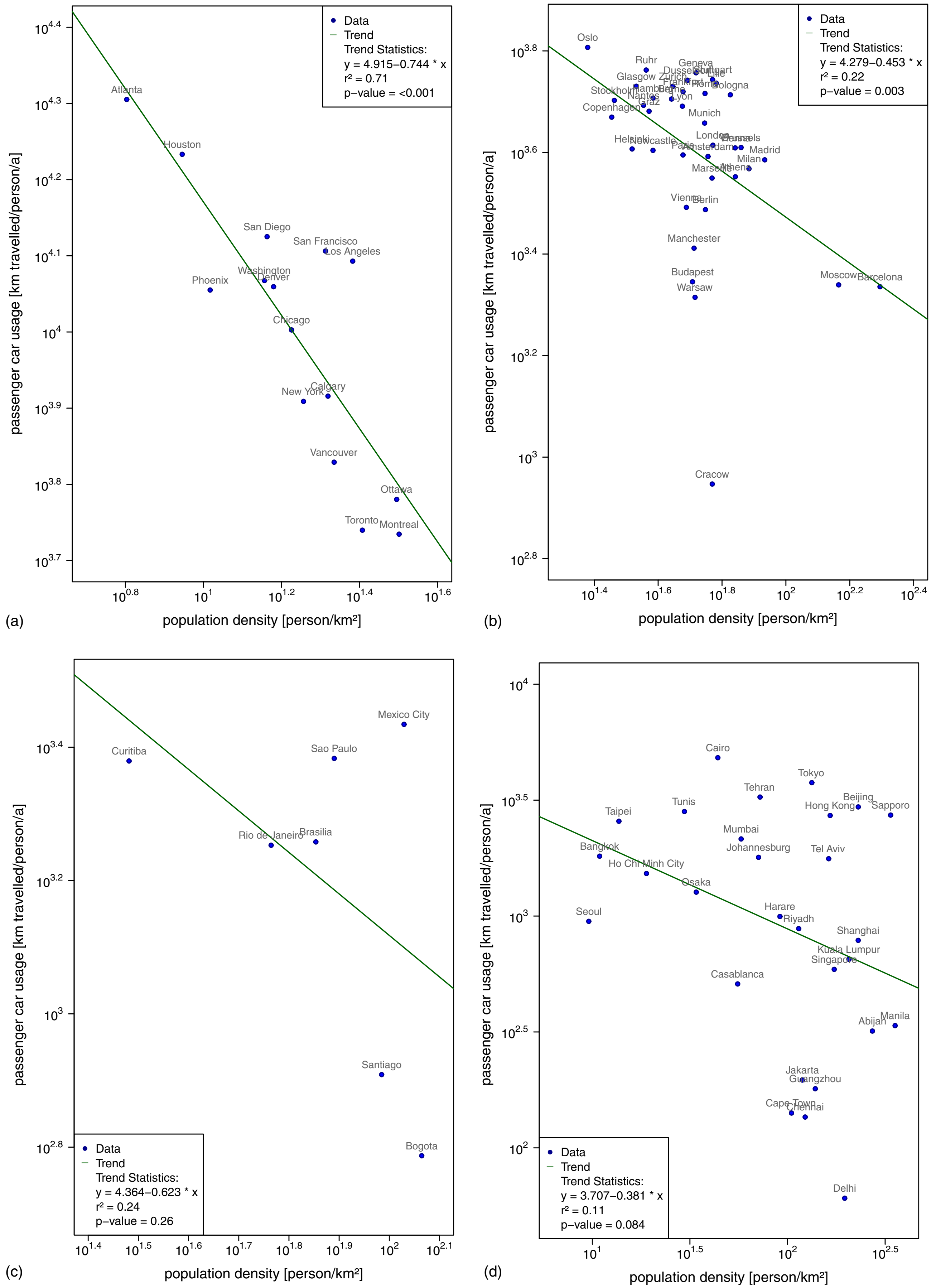

Fig. 1. Population density affecting gasoline consumption for various cities, shown as linear correlations in plots with logarithmic axes: (a) 15 North American cities; (b) 38 European cities; (c) seven South American cities; (d) 28 Asian cities [created from data from Kenworthy and Laube (1996)]

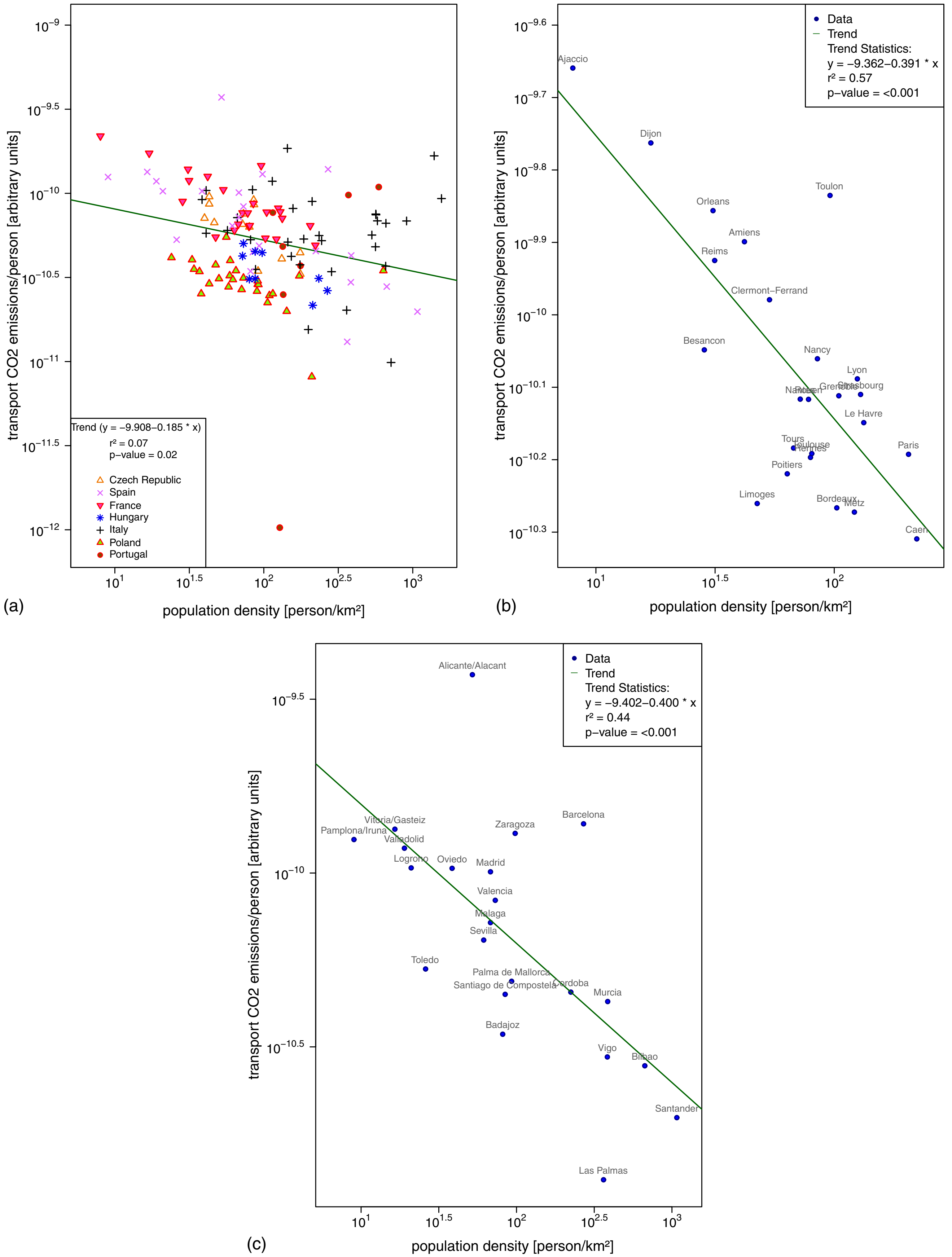

Fig. 2. Population density affecting CO_2 emissions from ground transportation for various cities; median data shown as linear correlations in plots with logarithmic axes: (a) 134 European cities; (b) 24 French cities; (c) 22 Spanish cities [created from data from Balk et al. (2005)9. European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL) 2009]

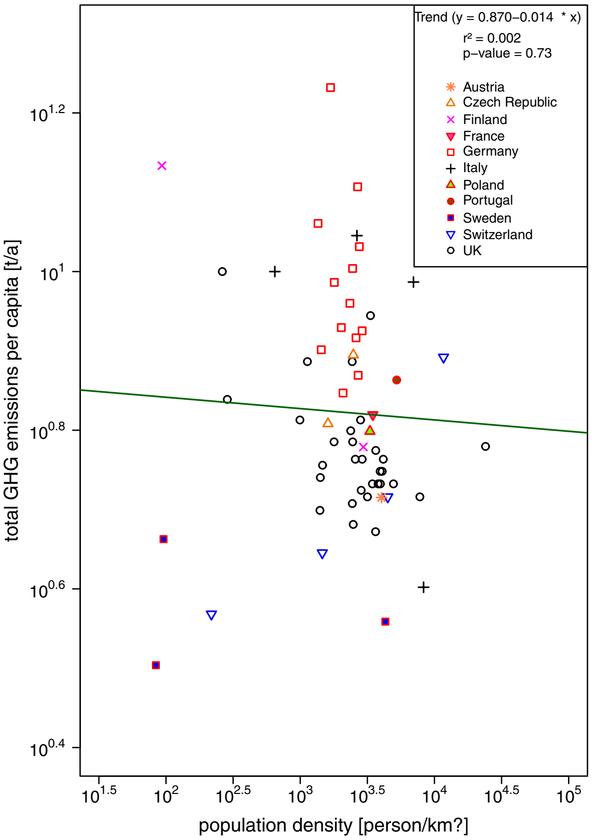

Fig. 3. Population density affecting urban GHG emissions for 62 European cities [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production), shown as linear correlation in a plot with logarithmic axes; a list of the analyzed cities is provided in Table 1]

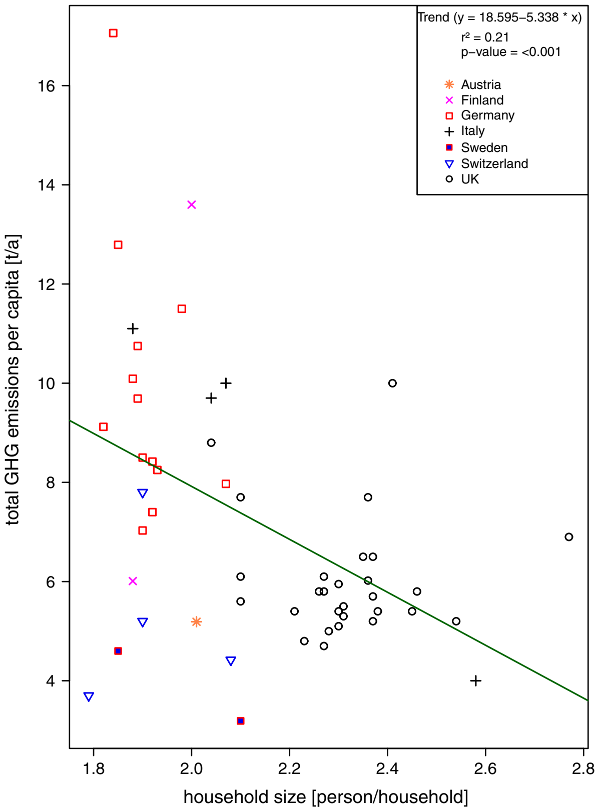

Fig. 4. Household size affecting urban GHG emissions for 54 European cities [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production); household size refers to the number of people living in one household; a list of the analyzed cities is provided in Table 1]

of the personal purchasing power on the amount of CO_2eq emitted per person. All other additionally introduced variables did not show significant effects on the amount of a person's total GHG emissions.

Impacts of Scales, City Sizes, and National Energy Concepts

It has been shown that the scale of the focus matters when analyzing transport GHG emissions. Hence, this finding was also investigated for total urban GHG emissions.

Therefore, analyses were conducted, not only for the European level, but also for the sub-European and national levels. The sub-European level was introduced to determine whether there are certain detectable clusters of cities that are not bound to national specifics, but that are less visible on the European scale. A city type was identified that represents the highest CO_2eq emissions per capita, the lowest population density, the smallest household size, the highest PPS, the lowest population growth, and the second highest change of PPS over time. Thus, although this finding was statistically not significant, it shows the influence of income, household size, and population density on GHG emissions on a sub-European level.

Because of the high standards that were laid on the GHG emission data (Scope 2 emissions, including upstream emissions for energy production, final energy consumption-oriented assessment methodology, and latest data), an analysis of total urban GHG emissions on a national level was only possible for the U.K. (30 cities) and Germany (10 cities).

U.K.

In the U.K., population density is the most significant driver of urban GHG emissions; an inversely proportional relationship is identified between decreasing urban CO_2eq emissions and increasing population density ($r^2 = 0.23$; p-value $=< 0.01$). Additionally, multiple regression analyses indicate that personal wealth combined with population density (both in an inverse proportional relationship with GHG emissions) is even stronger in determining the amount of CO_2eq emitted ($r^2 = 0.46$; p-value $=< 0.01$). Both variables significantly contribute to this result (p-value $=< 0.01$). Thus, national investigations for the U.K. fully support the assumption that the scale of analysis matters.

Germany

Because of lower data quantity, findings were expected to be less obvious than those for the U.K. Indeed, results were not statistically significant, but only pointed to a possible influence of population change over time ($r^2 = 0.39$; p-value $= 0.05$; $\alpha = -0.23$). Furthermore, a model consisting of personal wealth, population density, and household size (all inversely proportional to GHG emissions) was identified as most appropriate (however, not significant) for determining GHG emissions in German cities ($r^2 = 0.51$; p-value $= 0.08$). Hence, both wealth and household size seem to have an influence on the per capita CO_2eq emissions in German cities. Although not significant, an increase in the importance of

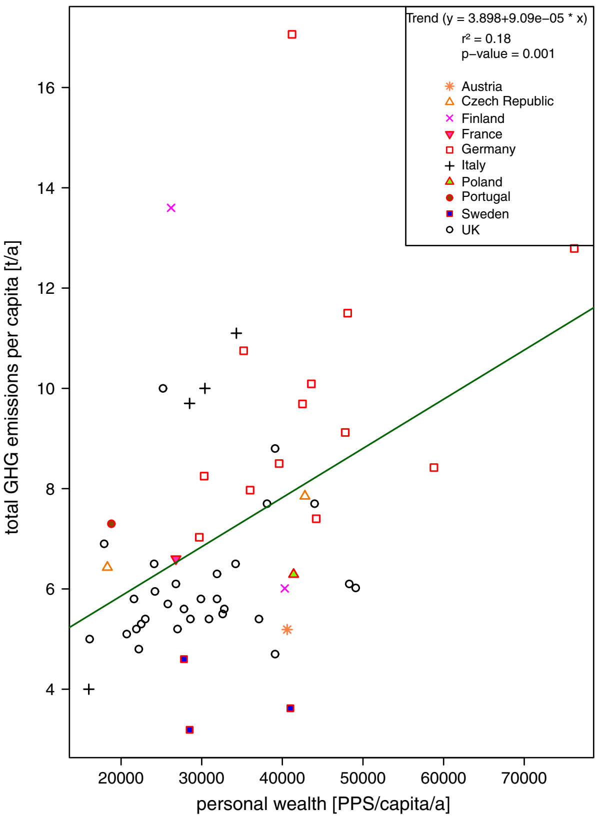

Fig. 5. Personal wealth affecting urban GHG emissions for 58 European cities [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production); personal wealth is reflected by information about PPS; a list of the analyzed cities is provided in Table 1]

population density could also be recognized on the German level compared to the continent level.

In general, findings on the national level support the previous assumptions: certain important drivers of GHG emissions on the global scale, which had not been found to be strong determinants of CO_2eq emissions on the European level, were identified as more influential in the national arena (such as population density). Furthermore, analyses of U.K. and German cities support the observation that personal wealth and household size are highly important for controlling the amount of urban GHG emissions.

Apart from the scale of analysis, two further distinct characteristics of urban areas directly impact their GHG emissions.

1. The size of a city is often related to a specific role or function of the urban area within the regional or even national context (Stead and Marshall 2001).
2. The carbon intensity of a city's electricity production becomes especially important in times when nations strive toward a more sustainable and climate friendly development, because urban areas, as "islands of development," consume extraordinarily high amounts of electricity, thus playing an important role in a nation's concept of sustainable development.

Taking both matters into account, the data were further clustered according to city size (in terms of population size) and data corrections were performed with regard to the varying CO_2 intensities of the electricity production of cities [following Hoornweg et al. (2011), it was assumed that the energy mix of cities is similar to the energy mix of the host country]. The resulting "corrected" data set provided information for four different city types: small cities (five cities with 1 to 100,000 inhabitants), medium cities (36 cities with 100,001 to 500,000 inhabitants), large cities (15 cities with 500,001 to 1,000,000 inhabitants), and million cities (six cities with >1,000,000 inhabitants). Furthermore, the GHG emission data of all cities were presented with a uniform CO_2 intensity for their electricity production. Thus, the source of a city's energy production does not matter, e.g., hydropower or burning coal.

The results also indicate that the size of a city matters. Whereas the influence of household size was shown to be a strong determinant of urban GHG emissions at the European level, clustering for city sizes showed that this is especially dominant in cities with a population between 500,001 and 1,000,000 inhabitants ($r^2 = 0.61$; p-value $=< 0.01$). If it is additionally corrected for varying CO_2-intensive electricity production methods, household size and GHG emissions show a significant inverse proportional correlation. This is true on the European level and even more pronounced for medium and large European cities (Fig. 6). For small and million cities, similar findings can be found. However, because of very small data sets, the significance of these findings should be questioned.

Therefore, if the data are analyzed in more detail, an effect of the specific city size is detectable. Furthermore, if the data are corrected for different electricity production types, the influence of household size is even more pronounced. Moreover, this influence on GHG emissions is inversely proportional, rather than linear (as initially expected).

Discussion

Reinvestigating the observations of NK and KEN for European cities, it is found that the geographical scope of analysis crucially influences the correlation of population density with GHG emissions; also, a significant role of household size and personal wealth is identified to influence GHG emissions. As already mentioned, this statistical significance is also given (statistical p-values $<$ 0.01), although the constructed linear model cannot be fitted well (low statistical r^2-values).

Controlling Urban GHG Emissions: The Importance of Population Density

NK and KEN found that population density strongly determines urban GHG emission. Two concerns can be raised. The first point refers to the data collection method. NK and KEN concentrated on the largest and most important cities in the countries, which may raise problems related to a similar function and role of these cities in the national context. Therefore, one might assume that the cities under analysis are also similar in important urban properties, such as crucial urban structures, urban economy, transportation design, or city and population size (Stead and Marshall 2001). Second, as Mindali et al. (2004) stated, NK's "… data collection method […] is subject to inconsistencies due to different definitions used by the respondents and inaccuracies resulting from an attempt to recollect data for a period 20 years earlier…" (Mindali et al. 2004, p. 160). Considering these weaknesses, this study focused on European cities of various city sizes (and national importance) and attached great importance to a sound and consistent data set. Supporting this analysis, biasing effects were additionally considered of varying city sizes, energy supply systems, or latitudinal distribution.

Further criticism may be related to the size of the data sets under analysis. Whereas NK draw their conclusions from analyzing 88 global cities in the 1996 data (only 32 cities in their original

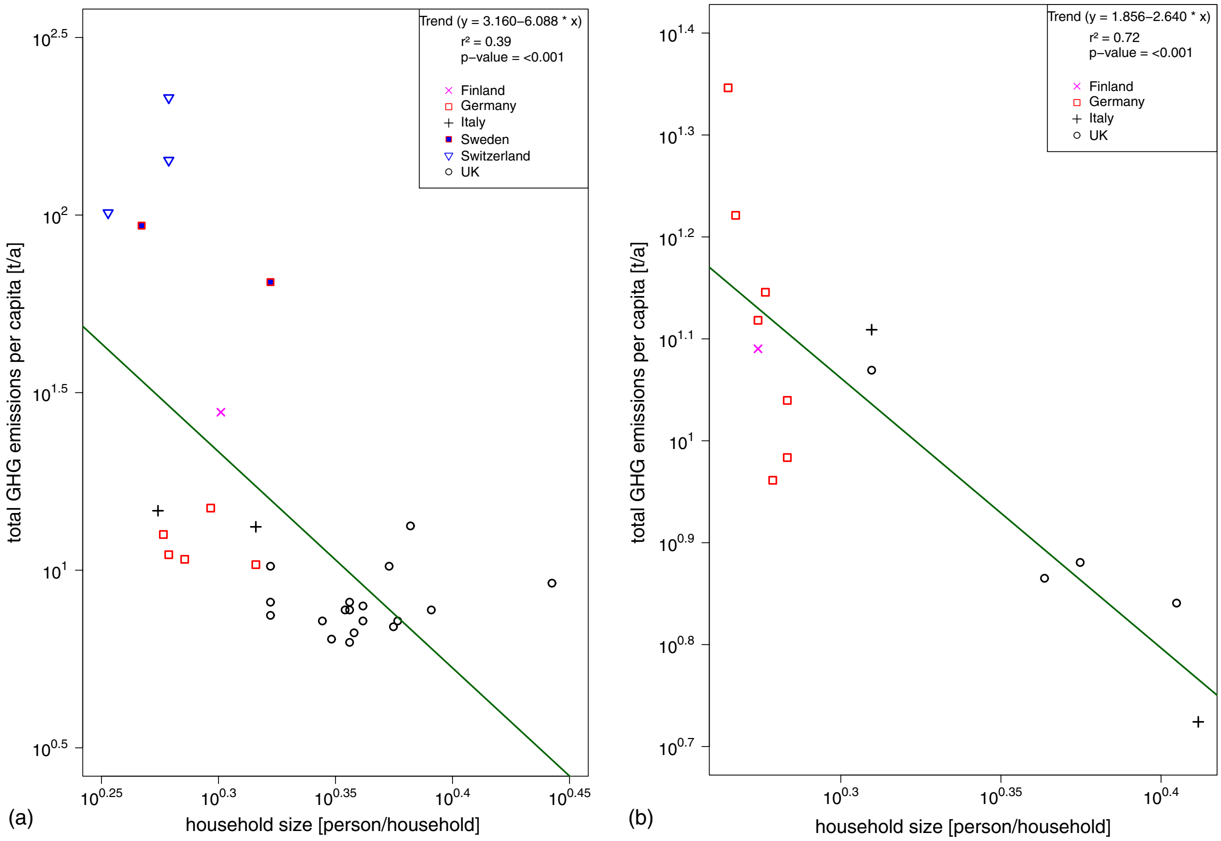

Fig. 6. Household size affecting urban GHG emissions for: (a) 31 medium-sized European cities; (b) 14 large European cities; [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production) and assume similar CO_2 intensities of electricity production; household size refers to the number of people living in one household, shown as linear correlations in plots with logarithmic axes; a list of the analyzed cities is provided in Table 1]

publication in 1989), KEN statistically investigated only 10 cities worldwide. However, on a global scale, possible influential forces such as temperature regime, personal wealth, or population density vary widely, and thus, require large data sets for sound statistical results. Therefore, it is questionable whether the data sets of NK and KEN were sufficiently comprehensive to conduct thorough statistical analyses on a global scale. In contrast, the European data sample introduced in this study contained comparatively more cities (134 for the analysis of transportation GHG emissions and 62 for total urban GHG emissions). Nevertheless, a smaller geographical scale also leads to less variation within the data set. Hence, it may be assumed that the influence of population density on CO_2eq emissions is simply less detectable in the current data than it is in the global data of NK and KEN.

The presented data for transport GHG emissions were created by joining different data sources, which often leads to small inaccuracies (e.g., with regard to resolution). GPW data were joined for population density and EDGAR data for transport CO_2 emissions; both data sets were obtained from trustworthy sources and are explicitly recommended for use in research and policy-making. However, the GPW data vary in spatial resolution, showing worse data quality for certain countries. This problem was addressed by limiting the analysis to countries with appropriate spatial resolution.

Also, an analysis of all urban GHG emissions did not support NK's finding for the European level. Postulating that these data are more comprehensive than data exclusively on transport GHG emissions (Kennedy et al. 2009b), it is assumed that the influence of population density may simply be less obvious in total urban GHG emission inventories and that the relevance of population density for controlling CO_2eq emissions may be dampened by other GHG determining factors at certain scales.

Therefore, the influence of population density is less visible at the European level than at the national level. In contrast, country-specific circumstances may either foster the influence of population density on GHG emissions (e.g., U.K., France, and Spain) or show the stronger importance of other factors (household size and personal wealth) on the amount of GHG emissions. In this respect, slightly different GHG determinants were identified than in the KEN study, which is mostly attributed to different data sets and varying analysis methods [KEN separately analyzed emission data for electricity consumption, fuel consumption for heating and industrial processes, and transportation (Kennedy et al. 2009a)].

Controlling Urban GHG Emissions: The Influence of Temperature Regime, Household Size, and Personal Wealth

KEN found that the specific temperature regime (in terms of HDD) is an important determinant of urban GHG emissions in global cities. For European cities, however, such a strong influence of HDD was not found. Moreover, the findings showed strongly opposing statistical signals. The reasons for this difference may be related to the data under analysis, because the GHG data were corrected beforehand for seasonal variations by city commissioners, which is supposed to lead to a removal of the influences of a changing temperature regime on CO_2eq emissions. To support this assumption, the importance of the HDD data were additionally analyzed on the national level (not presented in the paper). This also did not lead to statistically significant results, but underlines the influence of city commissioners' data correction because it also excludes a biasing effect caused by the latitudinal distribution of the European cities. On the other hand, KEN analyzed CO_2eq emissions from heating and industrial processes only. In contrast, data were used in this study that additionally included emissions from transport and energy sectors (Scope 2 and upstream emissions).

Furthermore, the scale and scope of analysis may be crucial, especially for analyzing the effect of a temperature proxy on the amount of GHG emissions from heating and cooling processes. In this respect, this study concentrated mostly on central European cities (considering that many data came from the U.K. and Germany), whereas KEN focused only on 10 different cities from all over the world. Hence, their differing conclusions might also be attributable to a larger data set and a smaller variation in the HDD data (a temperature influence on GHG data would have been less obvious in the presented analysis than in the KEN analysis).

Analyses showed that total urban CO_2eq emissions in the investigated 62 European cities are strongly determined by the size of a household. This finding was confirmed by simple and multiple regression analyses, which emphasizes the importance of household sizes for controlling urban GHG emissions. Although an influence of household size on per capita GHG emissions was expected (because of energy and heating sharing and the possibility for joint transportation), the significance of this impact on total European urban GHG emissions is remarkable. To date, the authors are not aware of any other analysis that showed a similar importance of household size for managing urban GHG emissions.

In this respect, it is also important to consider nationally specific characteristics. Whereas German cities are generally made up of smaller households, urban dwellers in the U.K. live in larger households. This might be attributable to the general spatial situation of a country and its impacts on society's development. For instance, the combination of the U.K.'s limited possibilities for spatial expansion (because it is an island state) and its increasing levels of immigration have resulted in a generally higher population density than in other EU countries (Khan 2008), especially in urban areas (Easton 2008).

Furthermore, some cities are negatively diverging from the discovered trend. These cities are primarily located in Austria, Switzerland, Sweden, and Finland, and present the urban dwellers with the lowest GHG emissions in the European study. In this respect, all of these nations use water power (Austria and Switzerland), nuclear power (Sweden), or both (Finland) to generate electricity. Thus, they have less CO_2-intensive energy production than other European countries (Oesterreichs Energie and Eurelectric 2012), which explains their negative divergence from the trend found in Fig. 4. To further investigate the influence of different energy production methods, the GHG emission data were corrected for the varying energy CO_2 intensities of cities, which resulted in modified urban GHG emission data with uniform GHG intensities for the production of electricity. Additionally, different city sizes were clustered to prevent a bias from a city's national function. An analysis of these modified data demonstrated that household size is a key driver of European urban GHG emissions and that the form of its influence is dependent on the specific city type. Whereas GHG emissions of cities generally showed a linear correlation with household size across Europe, this relationship is inversely proportional rather than linear, if the data are corrected for differing energy CO_2 intensities. This is especially true for medium and large urban centers.

Therefore, it is assumed that the actual relationship between household size and GHG emissions per capita is truly inversely proportional, but simply appears as a linear relationship on an overall European level. This may be attributable to the level of data detail and the use of different energy carriers for energy production.

Analyses suggest that the personal wealth of an urban dweller is another important determinant of European urban GHG emissions (higher standard of living results in higher total GHG emissions per capita). This finding offers some new and interesting insights. Transport GHG emissions were observed to increase with rising income (mode change to private transport for reasons of travel time, status, and longer distances traveled) (Creutzig et al. 2012b; Lankao 2007; Newman and Kenworthy 1989; Reckien et al. 2007; Schäfer et al. 2009; Sinha 2003). Particularly for heating, this trend was less clear [according to Brown (1984) and Gabriel et al. (2010) because of various reasons; for instance, housing retrofits may be less accessible for poorer citizens]. However, the findings now assume that a higher overall PPS significantly increases the amount of CO_2eq emissions per urban dweller. This was detected at the European level and indicated at a national level.

Conclusion and Outlook

This paper presented an empirical analysis of the primary drivers of GHG emissions in European cities. Therefore, the well-known findings by NK and KEN (that population density is inversely proportional to transport CO_2 emissions) were investigated for 134 urban areas. Additionally, further socioeconomic variables, which are also assumed to be important determinants of urban GHG emissions, were empirically analyzed for 62 European cities. For this purpose, a comprehensive data set was created that contained information on total urban GHG emissions, independent of the specific energy production sites and methods or the energy carrier used in cities.

It was found that population density affects the amount of transport CO_2 and, thus, the amount of total urban GHG emissions. However, it is argued that both the significance and form of this relationship strongly depend on the scale of both the significance and form of this relationship strongly depend on the scale of analysis, as they cannot confirm NK's and KEN's postulated strong inverse proportional relationship. Possible reasons are expected to be related to data quality and quantity, and to city specific properties that are determined by geographical (e.g., temperature regime) or socioeconomic (e.g., living habits) influences.

Future analyses should substantiate this assumption and try to underpin this possible scale effect with larger data sets and further scales. In this respect, some results, showing a possibly comparable importance of population density on the city level, were provided in 2002 for three large urban areas in the U.S. (Holtzclaw et al. 2002) and in 2006 for two Australian cities (Newman and Kenworthy 2006).

Despite a strong research interest in analyzing population density for controlling urban GHG emissions (Stead and Marshall 2001), it is shown that further important drivers should be considered. The size of a household affects the amount of total European urban GHG emissions. Hence, it can be concluded that if more people live together, the overall CO_2eq emissions per capita can be significantly reduced (inversely proportionally decreasing). This is shown to be especially applicable in medium (100,001 to 500,000 inhabitants) and large (500,001 to 1,000,000 inhabitants) European cities. Furthermore, a higher standard of living is not only related to a more CO_2 intensive transport habit, but also results in higher CO_2eq emissions overall. Hence, the assumption that richer people produce less GHG emissions because they use more resource-efficient products and live in better insulated homes should be revised, at least for European cities. Therefore, more thorough analyses are encouraged of the role of household size and personal wealth for effective reduction of urban GHG emissions. This is also important because some of the presented statistical models revealed interesting significant relationships, but may need further refinement. Furthermore, investigating the possibility of using information about PPS instead of GDP as a proxy for personal wealth and standard of living is encouraged because PPS may be more appropriate than GDP for analyses that investigate international income data. In the end, it may be of prime importance to find additional ways to control urban GHG emissions, because implementing NK's recommended "densification" of cities could lack sufficient support because many citizens may not want to live in high-density neighborhoods (Breheny 1995). Therefore, future analyses should also consider the city-specific temperature regime and investigate interactions between possible GHG determinants, especially when trying to comprehensively understand a city's GHG emission drivers.

In the end, the presented results are bound by data quality and quantity, both of which may be insufficient to uncover all relevant details at all spatial scales. Hence, this study encourages further spatially explicit econometric research and detailed causal models of urban areas. In this respect, it is shown that it is essential to take city-specific properties (such as electricity production methods or the role of the city in the regional or national context) into account and to use a sound, comparable, and comprehensive data set that also includes CO_2eq emissions that are not directly produced within the city.

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