Greenhouse Gas Emissions in European Cities:

A straightforward approach for estimating urban emissions by focusing on relevant socioeconomic and spatial drivers

vorgelegt von

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To Angelika

Prelude

Climate change threatens hard-won peace, prosperity, and opportunity for billions of people.
No one is immune from climate change.

Today we must set the world on a new course.
Climate change is the defining issue of our age. It is defining our present.
Our response will define our future.

To ride this storm we need all hands on deck.
That is why we are here today. We need a clear vision.
The human, environmental and financial cost of climate change is fast becoming unbearable. We have never faced such a challenge.
Nor have we encountered such great opportunity.

A low-carbon, climate resilient future will be a better future.
Cleaner. Healthier. Fairer. More stable. Not for some, but for all.

There is only one thing in the way.
Us. We.

We must cut emissions. We must invest in climate-resilient societies that protect all, especially the most vulnerable. Economists have shown that this comes at minimal extra cost, while the benefits to our people and our planet are monumental.

All these actions demand collaboration, cooperation and coalitions.

That is why we are here today.
We are not here to talk. We are here to make history.

Based on
Ban Ki-moon's opening remark at 2014 Climate Summit

Climate change is real and global mean temperatures are rising, culminating in constant new weather records for hottest days (Commonwealth of Australia, 2014), months (Holthaus, 2014) and even years (Bojanowski, 2015; Deng, 2015).

Global warming of land surfaces and oceans (Novak, 2015) is not a distant fiction anymore, but has already become a real threat to human beings, animals and plants (Cole et al., 2015; European Environment Agency, 2014; Kessler, 2014b; Steffen et al., 2015). Hardly any doubt is left that global temperature increases of up to 0.8°C to date[1] are mainly caused by anthropogenic activities related to the burning of fossil fuels[2] (The World Bank Group, 2014a; IPCC, 2014a).

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), and the commonly agreed-upon goal of limiting the mean global temperature increase to 2°C is at risk if additional mitigation actions are further delayed (IPCC, 2014a; Steffen et al., 2015).

If it is not possible to reach this target, profound changes to landscapes and oceans are expected (The World Bank Group, 2013). Furthermore, specific natural tipping points might be triggered that will lead to self-intensifying climatic changes. Although climate change is a global phenomenon, its threats will be local and unevenly distributed. In particular, poorer nations (developing and least developed countries) will have to cope with the strongest influences, such as with severe water shortages and droughts (e.g., in the Mediterranean region, South-America or Sub-Saharan Africa) or rapid sea level rise (e.g., island states such as the Maldives or the Marshall islands or low lying countries such as Bangladesh). These climate change impacts will make it harder to survive locally, but also affect global processes (e.g., food production).

Therefore, urgent action is needed to limit further global warming. The biggest climate change drivers need to be identified and uncontrolled emissions of CO_2 must be hindered. In particular, considering the prospect of large investments in global infrastructures, more sustainable development strategies must be implemented (The New Climate Economy, 2014). Concurrently, strategies need to be developed globally that help people adapt locally to already induced climatic changes, particularly in cities (European Environment Agency, 2012; IPCC, 2014b; Masson et al., 2014).

By analyzing urban influences on CO_2 emissions, this thesis aims to reveal insights into their possible reduction. In the end, these findings can help to cut global greenhouse gas emissions and thus mitigate future climatic changes.

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[1] 2003-2012 compared to 1850-1900.

[2] For example for energy production, heating, or transport.

Summary

Climate change is one of the most pressing challenges of the 21st century. As cities are responsible for the majority of global greenhouse gas emissions, they are a crucial driver of climate change. Additionally, they will have to cope with severe impacts related to their high population and infrastructure densities. Hence, urban areas are internationally recognized focal points for climate change actions.

However, more knowledge is required on the actual urban climate influences, and on most effective measures for curbing cities' greenhouse gas emissions. Urban areas must be made aware of their own emission context, including their important emission drivers. Currently existing approaches for greenhouse gas inventorying, however, are too complex for cities with limited climate change competencies.

To this end, this thesis aims at developing an easier approach for estimating urban greenhouse gas emissions in order to initiate appropriate emission reduction strategies. Therefore, socioeconomic and demographic emission influences are analyzed for 62 European cities, and thorough spatial analyses of the urban layout and land use and land cover patterns are conducted. By investigating both dimensions, the most significant urban emission drivers are identified and jointly utilized for estimating urban greenhouse gas emissions.

Among various potential influences, in particular the socioeconomic variable "household size" and the spatial variable "edge density of the discontinuous dense urban fabric" are found to have the greatest impacts on urban emissions. Both variables scale inversely to emissions and can be combined in a multiple linear regression model to explain 86% of the total greenhouse gas data. Urban sprawl is also found to significantly counteract initiatives to lower urban emissions. In this context, particularly intra-urban distributions and compositions of land use and land cover classes matter, as well as the CO_2 intensity of the electricity production.

Cities should consider these emission influences when planning comprehensive climate change actions. It is shown that both main emission drivers can be addressed, without restricting future climate change adaptation measures. Additionally, urban areas with limited awareness about their climate impact can use the developed approach for gaining insights into their own emissions. Future research should extent this knowledge on important urban emission influences and partner cities in developing the methodologies further and refining the presented emission estimation approach.

Zusammenfassung

Der Klimawandel ist eines der drängendsten Probleme des 21. Jahrhunderts. Städte sind verantwortlich für den Großteil der globalen Treibhausgasemissionen und sind somit zentrale Klimawandeltreiber. Da sie gleichzeitig Bevölkerungs- und Infrastrukturzentren darstellen, werden sie besonders mit den Folgen des Klimawandels konfrontiert werden.

Dennoch ist das Wissen über ihren genauen Einfluss auf das weltweite Klimasystem noch lückenhaft. Speziell weitere Erkenntnisse über die effektivsten Emissionsminderungsmaßnahmen werden benötigt. Hierzu müssen sich Städte ihrer „Emissionssituation“ und ihrer wichtigsten Emissionseinflüsse bewusst werden. Die zu diesem Zweck entwickelten Ansätze zur Emissionsberechnung sind jedoch zu komplex und daher oft nicht praktikabel.

Daher entwickelt diese Doktorarbeit einen einfacheren Ansatz zur Abschätzung urbaner Treibhausgasemissionen. Hierzu werden zuerst die bisher als wichtig erachteten sozioökonomischen und demographischen Emissionseinflüsse für 62 Europäische Städte untersucht. Räumliche Analysen der städtischen Struktur und der Landnutzung bzw. Landbedeckung geben zudem Aufschluss über Zusammenhänge zwischen räumlichen Stadteigenschaften und Emissionen. Erkenntnisse über die wichtigsten Emissionseinflüsse aus beiden Analysen werden dann verwendet, um ein einfacheres Modell zur Abschätzung urbaner Treibhausgasemissionen zu entwickeln.

Es zeigt sich, dass vor allem die „Haushaltsgröße“ und die räumliche Variable „Kantendichte der diskontinuierlich dichten Stadtareale“ (*Edge density of discontinuous dense urban fabrics*) im starken, logarithmischen Zusammenhang mit städtischen Emissionen stehen. In einem linearen Regressionsmodell erklären sie zusammen 86% der gesamten Streuung der analysierten Emissionsdaten. Ebenso wird deutlich, dass „urban sprawl“ zu höheren Emissionen führt. Auch die innerstädtische Verteilung der Landnutzungsklassen, genauso wie die CO_2 Intensität der Stromerzeugung spielen hierbei eine wichtige Rolle.

Städte sollten diese Emissionseinflüsse für umfassende Klimawandelmaßnahmen beachten. Dies erscheint auch möglich, wenn Anpassungsmaßnahmen an den Klimawandel notwendig werden. Speziell bei noch geringem Klimawandelwissen kann der entwickelte Ansatz helfen, tiefergehende Erkenntnisse über die städtische Klimawirkung zu gewinnen. Zukünftige Forschung sollte diese Erkenntnisse zusammen mit städtischen Partnern ausbauen und die vorgestellten Methoden weiterentwickeln.

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List of Abbreviations and Acronyms

AIC	Akaike's information criterion
CBD	Central business district
CC	Climate change
CDD	Cooling degree days
CO2	Carbon dioxide
CO2eq	Carbon dioxide equivalents
CUF	Continuous urban fabric
DDUF	Discontinuous dense urban fabric
DG	Directorate-general
ED	Edge density
EDGAR	Emissions database for global atmospheric research
EU	European union/ Europe (German: Europäische union/ Europa)
GHG	Greenhouse gas
GPW	Gridded population of the world
HDD	Heating degree days
HH	Household size
IPCC	Intergovernmental panel on climate change
LULC	Land use and land cover (German: Landnutzung und Landbedeckung)
LUZ	Larger urban zone
MPE	Mean patch edge
MPS	Mean patch size
NumP	Number of patches
PUSH	Parameter of urban shape complexity
TE	Total edge
THG	Treibhausgas
UA	Urban atlas project
UAT	Urban audit project
UHI	Urban heat island
UNFCCC	United nations framework convention on climate change

Part I

Introduction

I-1 Urbanization trends and cities' climate change relevance

The global human population now surpasses 7 billion inhabitants (United Nations, 2011), more than 53% of which live in urban areas (The World Bank Group, 2014b; United Nations, 2014). The most urbanized regions are North-America (82 % of population living in cities), Latin America and the Caribbean (80%), and Europe (72%). However, while population growth for US or European cities is slowing or even declining[3] (Kabisch and Haase, 2011; Oswalt, 2004; Wiechmann and Pallagst, 2012), medium-sized urban centers in Africa or Asia[4] are rapidly growing (United Nations, 2014).

Thus, while there were 10 megacities (>10 million inhabitants) in 1990 (mostly in more developed, northern countries) there are 28 megacities in 2014 (mostly in the global South) and it is expected that there will be 41 comparable cities in southern nations by 2030 (United Nations, 2014). Consequently, it is expected that more than 66% of the global population will be living in cities by 2050 (United Nations, 2014).

As a consequence of these global trends, urban demands for natural resources and ecosystem services such as freshwater, clean air, or recreational areas are increasing (Douglas, 2012). At the same time, cities are expanding physically into natural land, changing land uses and the land cover, which intensifies environmental stresses and pollution (Alberti, 2008; Yang et al., 2011). Furthermore, urban activities drive the majority of global energy use (European Institute For Energy Research, 2015) and account for more than 75% of the world's energy-related CO_2 emissions (IPCC, 2014c).

However, being highly dynamic systems (Kantro, 2014), cities can also be hubs for the development of more sustainable, climate-friendly lifestyles (Ala-Mantila et al., 2014; Glaeser and Kahn, 2010; Hoornweg et al., 2011a). Given these roles, strategies must be developed for cities to tackle the twofold challenge of reducing their climate effects and increasing their resilience to current and future climatic changes, such as heatwaves, flash-floods, sea-level rise or freshwater availability (Köferl, 2015; University of Cambridge Institute for Sustainability Leadership et al., 2014).

[3] In US 13% and in EU: 54% of all cities are shrinking.

[4] In medium-sized urban centers in Africa or Asia urban growth rates exceed 6%, triggered by the highest overall population growth rates and expected better living conditions in cities, compared to rural areas.

In order to reach these goals, a better understanding of the climate impact of cities is required (Romero Lankao and Dodman 2011) and best practice examples must be derived to support the development of environmentally sustainable urban lifestyles (Powell, 2015). To come up with possible best practices, a uniform and comparable way of measuring and detecting urban greenhouse gas (**GHG**) emissions is needed. Such an approach should enable city planners and administrators to easily estimate their city's GHG emissions and compare the results with other urban areas. Therefore, it must consider the dynamics influencing each city's main GHG emissions, including transport activities, energy production as well as the urban lifestyles. As shown subsequently (Chapter I-2), parameters should be investigated that reflect socioeconomic and demographic[5], and spatial urban properties. It is expected that the consideration of both dimensions is required to comprehensively analyze a city's most important GHG emission influences (Chapter IV). This thesis investigates these two dimensions in order to identify indicators that best reflect the most important urban GHG emission drivers. Since this knowledge is a prerequisite for defining best practices for cutting urban emissions, this approach should also be adoptable by cities in order to both uniformly estimate and compare their GHG emissions.

[5] Subsequently summarized as "socioeconomic" for the ease of reading.

I-2 Urban GHG emission drivers - the state of scientific knowledge

As identified in the previous Chapters, curbing further GHG emissions is central for managing climate change. In this context, cities have been identified as crucial components that need to be included in international and national strategies (Heidrich et al., 2013; Reckien et al., 2014; Russo and Comi, 2011).

They not only emit most of the anthropogenically produced GHG emissions (United Nations Human Settlement Programme, 2011), directly affecting the intensity of future climatic changes (IPCC, 2014c), but "[also have] the unique ability to respond to [...] climate change at a local, more visceral level" (Hoornweg et al., 2011b, p.2). This is critical, as urban areas will inevitably have to cope with the impacts of changing climatic patterns due to their additive microclimatic characteristics (Hallegatte, 2009; IPCC, 2014b; McDonald et al., 2014; Patz et al., 2014). Moreover, cities can help to promote sustainable development and lifestyles, leading to lower GHG emissions (Ala-Mantila et al., 2014; Glaeser and Kahn, 2010; Hoornweg et al., 2011b). However, in order to do so, more knowledge is still needed on cities' actual contribution to climate change (Bergeron and Strachan, 2011; Hoornweg et al., 2011b; Romero Lankao and Dodman, 2011). Particularly regarding best practice examples on how to sustainably curb a city's biggest GHG emission sources, standardized and more applicable approaches are needed that integrate the most important emission drivers. Although such standards are currently being developed on the international level (Bhatia and Ranganathan, 2004; C40 Cities, 2012; United Nations Framework on Climate Change, 2007), easily reproducible approaches on the urban level are still missing. Therefore, indicators need to be investigated that broadly reflect a city's main GHG emission sources (Chapter I-5.2.1) and that take in particular a city's socioeconomic as well as its spatial properties into account (Part IV).

With regard to possible socioeconomic GHG influences, research has identified personal wealth, population density, household size, and heating or cooling requirements as notably affecting urban GHG emissions per capita (Ala-Mantila et al., 2014; Baur et al., 2013; European Environment Agency, 2012; Heinonen et al., 2011; Newman and Kenworthy, 1989; Zhang et al., 2010).

However, often driven by a lack of uniform data most of this research was limited in its scope, analyzing either small sets of cities or very similar urban areas. Consequently, their findings were disputed and could not always be confirmed in other studies. For example, an inversely-proportional relationship[6] between population density and transport energy consumption was identified by Newman and Kenworthy in 1989 for 32 primary global cities (Newman and Kenworthy, 1989). Further studies substantiated this correlation, especially within the US, showing a relationship between higher housing density and reduced heating-related emissions (Ewing and Cervero, 2010). However, other studies' reject population density as the primary driver of transport GHG emissions (Mindali et al., 2004) or deduce that population density is an important urban GHG emission determinant, but not the only one (Baur et al., 2013; Rickwood et al., 2008).

Realizing the potential relevance of urban compactness (Newman and Kenworthy, 2006; Kennedy et al., 2009a) apart from population density, other indicators were investigated to analyze the relevance of a city's form and structure on its environmental and climate impact (Creutzig, 2014; Feng and Li, 2012; Zhang et al., 2010). In this context, research focused on the issue of urban sprawl for cities in the US (El Nasser and Overberg, 2001; Ewing et al., 2007; Schneider and Woodcock, 2008), Europe (European Environment Agency, 2006; RWI et al., 2010), China (Deng and Huang, 2004; Feng and Li, 2012), and in other regions (Schneider and Woodcock, 2008). Furthermore, some studies utilized large sets of landscape metrics (Huang et al., 2007; Schwarz, 2010) for investigating the spatial layout of urban agglomerations. The results of these studies suggest that for analyzing the urban form, it is sufficient to focus on just a few indicators out of the numerous landscape metrics that have become available over the last years. Hence, particularly the edge density (**ED**), mean patch edge (**MPE**), mean patch size (**MPS**), total number of patches (**NumP**), and total edge (**TE**) should be considered (Schwarz, 2010).

Although the presented research complements this knowledge by revealing new insights regarding the spatial urban layout, explicit analyses of the linkage between urban spatial characteristics and GHG emissions are still missing. However, for a comprehensive understanding of a city's climate impact and for validating current knowledge about urban GHG emission drivers such investigations are urgently needed (Liao et al., 2013; Makido et al., 2012). Furthermore, the possible relevance of a city's land use and land cover (**LULC**) composition for controlling the GHG emissions of urban dwellers is still unclear. In this context, the relevance of the city center as a key point for urban growth and transportation dynamics must also be taken into account. Specifically, the areas referred to as "Central Business District" (**CBD**) should be considered due to their importance in the daily lives of urban citizens (Hartshorn, 1991). Although younger cities might also contain alternate focal points ("edge cities"), central urban areas (hereafter referred to as "city center") are still mostly represented by CBDs. They

[6] Subsequently referred to as "logarithmic relationship".

maintain an attraction for a large share of daily commuters (Maciag, 2014; Spiekermann, 1997) due to their concentration of monetary, cultural, and social values (Taubenböck et al., 2013; Rosenberg, 2014; Wang et al., 2014), and thus, by utilizing distance from the CBD as a GHG influence, might be relevant for analyzing urban GHG emission (Creutzig et al., 2012b; Rickwood et al., 2008).

This thesis aims at further closing this research gap. Therefore, various European (**EU**) cities of different urban characteristics (e.g., with regard to size and location) are analyzed to help to understand the impact of spatial urban structures and LULC compositions on the GHG emissions of urban dwellers. Various socioeconomic indicators are also re-investigated for their general relevance (considering various types of cities) for analyzing urban GHG emissions. In the end, statistical analyses are used to identify the dominant urban GHG emissions influences of both dimensions (socioeconomic and spatial). Utilizing these findings, an easily reproducible methodology is developed that can be used by cities to estimate their GHG emissions. This is an important step forward for finding best practices on how cities can sustainably lower their GHG emissions.

I-3 Overall research questions and research hypotheses

As previously elaborated, developing an approach that can be used by cities to easily and uniformly estimate their GHG emissions requires focusing on the most important GHG drivers. However, as cities' GHG emissions depend on various urban activities and processes, an analysis of multiple dimensions and data is necessary. Thus, both socioeconomic and spatial urban characteristics should be included in such a comprehensive urban GHG emissions[7] analysis.

To structure this analysis process, two overall research questions are formulated and three distinctive research hypotheses are defined to gradually develop an approach that includes only the most important GHG emission influences to estimate cities' GHG emissions:

Overall research questions:

1. Which socioeconomic and spatial urban characteristics have the strongest influence on cities' GHG emissions?
2. Is it possible to focus only on a few specific GHG influences to ease the estimation of urban GHG emissions?

Research hypothesis I: The socioeconomic drivers of urban GHG emission

The socioeconomic characteristics of the urban population are related to their daily activities and lifestyles (including transportation habits). Thus, they affect the amount of energy used (e.g., for transportation) and GHG emitted per capita. In particular, population density is expected to be strongly linked to urban GHG emissions per capita.

Research hypothesis II: The spatial drivers of urban GHG emission

Urban spatial characteristics influence cities' energy usage, and thus, their GHG emissions. More precisely, density-related urban characteristics and the intra-urban distribution and composition of various LULC classes are expected to be important emission drivers.

[7] "Urban GHG emissions" refers to "GHG emissions per capita", as this measure is more appropriate for analyzing cities of varying sizes (more information can be found in Chapter I-5.2.1).

Research hypothesis III: Limited requirements for estimating urban GHG emissions

Although a city's GHG emissions encompass different emission sources, estimating urban GHG emissions per capita can be accomplished by focusing on only a few socioeconomic and spatial parameters[8].

The investigation of all research hypotheses forms the main structure of the presented thesis (Chapter I-6) and answering the overall research questions defines its overarching goal. For a more general understanding, the following Chapters present in-depth information on the content and structure of this thesis.

[8] In this thesis, "parameter" is interchangeable with "variable" or "indicator".

I-4 Study area

Analyzing the introduced research hypotheses requires a comprehensive, multi-dimensional (GHG, socioeconomic, spatial) set of data. Therefore, potential study areas should be evaluated by the availability of these respective data types, as well as by their diversity in terms of city archetypes, and national and cultural differences.

Minding all of these requirements, the scope of analysis was set on EU cities. Thus, the extensive database from the EU could be utilized, including socioeconomic and demographic information (e.g., from the "Urban Audit" (**UAT**)- project), available in the Eurostat database (Eurostat, 2011a), as well as spatial data (from the "Urban Atlas" (**UA**)- project) that are uniformly collected across all EU members states (European Commission and Goulet, R., 2011). In this way, multiple nations could be included, reflecting cultural and geographical peculiarities (e.g., climatic regions).

For selecting the specific urban areas of interest, two main criteria were considered:

1. Comparable GHG emission data.
2. Differing population sizes.

As the main research goal was to analyze the dominant emission drivers of urban GHG emissions, the most important selection criterion was the availability of GHG emission data that included the same GHG emission sources for all cities. More information about the GHG data requirements and the final uniform dataset are presented in Chapter I-5.2.1.

With regard to the second criterion, cities of different population sizes were chosen to capture urban peculiarities that are linked to the specific city size[9] (Stead and Marshall, 2001).

In the end, the presented analysis covered 62 EU cities (Figure I-1), including small cities (1 to 100,000 inhabitants), medium cities (100,001 to 500,000 inhabitants), large cities (500,001 to 1,000,000 inhabitants), and million cities (>1,000,000 inhabitants). For all cities, uniform GHG data were available and for most urban areas socioeconomic and spatial data were available. More information about the particular cities under investigation for the analysis of specific research hypotheses can be found in the respective Parts II-IV.

[9] For example, the provision of public transport.

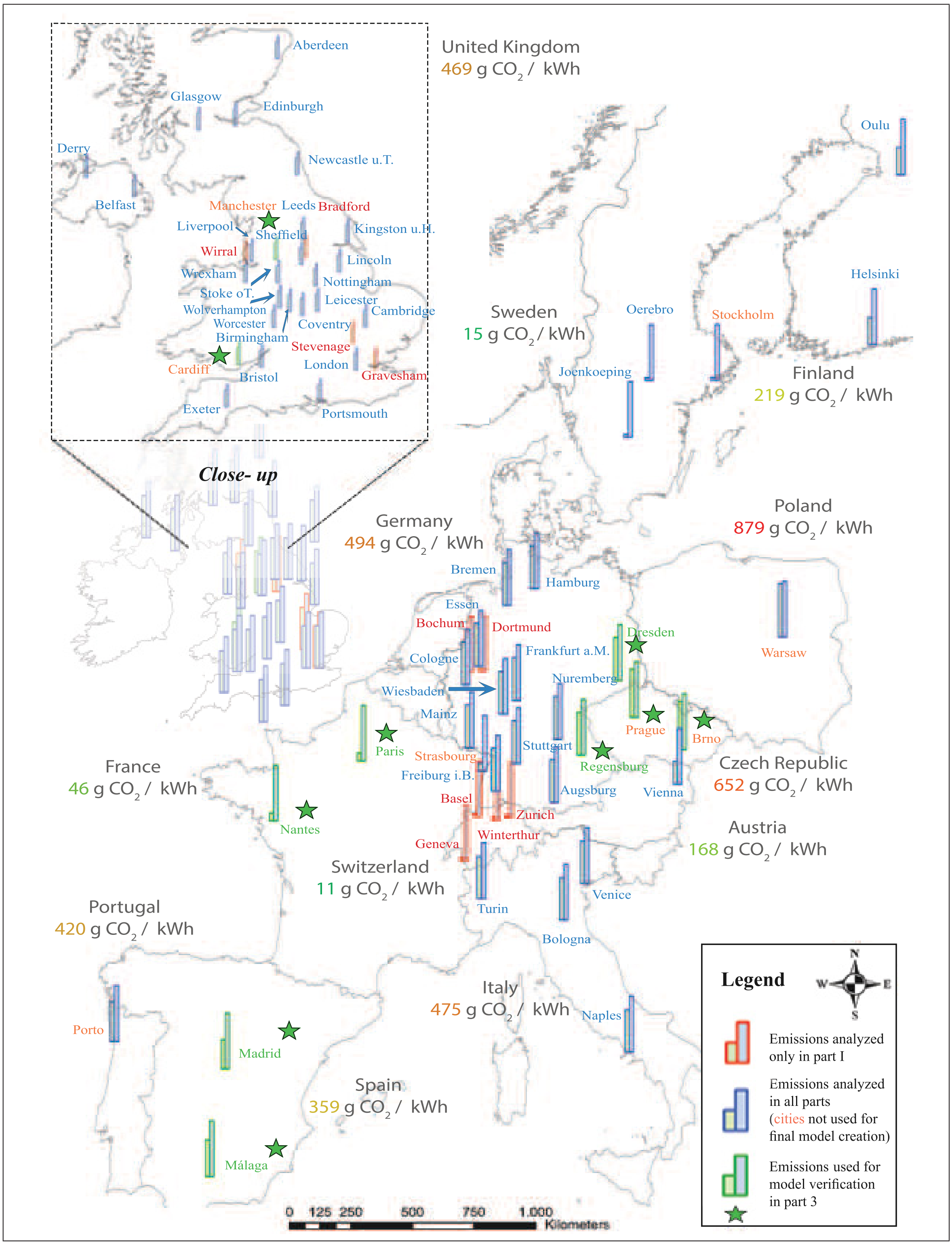


Figure I-1: Map of all analyzed EU cities, with color differentiation according to the analyses conducted (more information in Chapter V-4.1). Additionally, the effect of the correction for varying electricity CO_2 intensities (in g CO_2 / kWh) is indicated by corresponding bars (**left bar:** reported emissions; **right bar:** corrected emissions). Stars highlight urban areas that were used for verifying the final GHG model (Part IV)

I-5 Data and methodologies

To investigate the introduced research hypotheses, it is crucial to precisely define the scope of analysis and specify the particular data and processing needs. Therefore, this Chapter provides insights into the data and scientific methodologies used for analyzing EU cities' GHG emissions.

I-5.1 Definition of a city

Cities are not isolated agglomerations, but are linked to their surrounding areas (e.g., commuters work in the city but live in its surrounding areas). Therefore, an analysis of urban GHG emission requires a clear definition of the urban context in order to determine the activities and processes to investigate. The most common definitions include the "core city area", which corresponds to the official administrative boundaries (Figure I-2), or the "Larger Urban Zone" (**LUZ**) that also includes information on a city's commuting zone (European Commission, 2012).

Whereas recent input-output analyses of urban material fluxes and emissions focused on the LUZ (Duffy, 2009), this study analyzes a city with regard to its administrative city borders for two reasons:

1. The administrative city borders are more uniformly defined than LUZ in Europe and spatial information about their extent is mostly known to the city authorities (less for LUZ).
2. The available, EU-wide socioeconomic data from Eurostat (Eurostat, 2011a) are in reference to the administrative city borders.

Therefore, analyzing the core cities of all introduced EU urban areas (Figure I-1) was considered to be appropriate for investigating the most important (socioeconomic and spatial) GHG influences of EU cities.

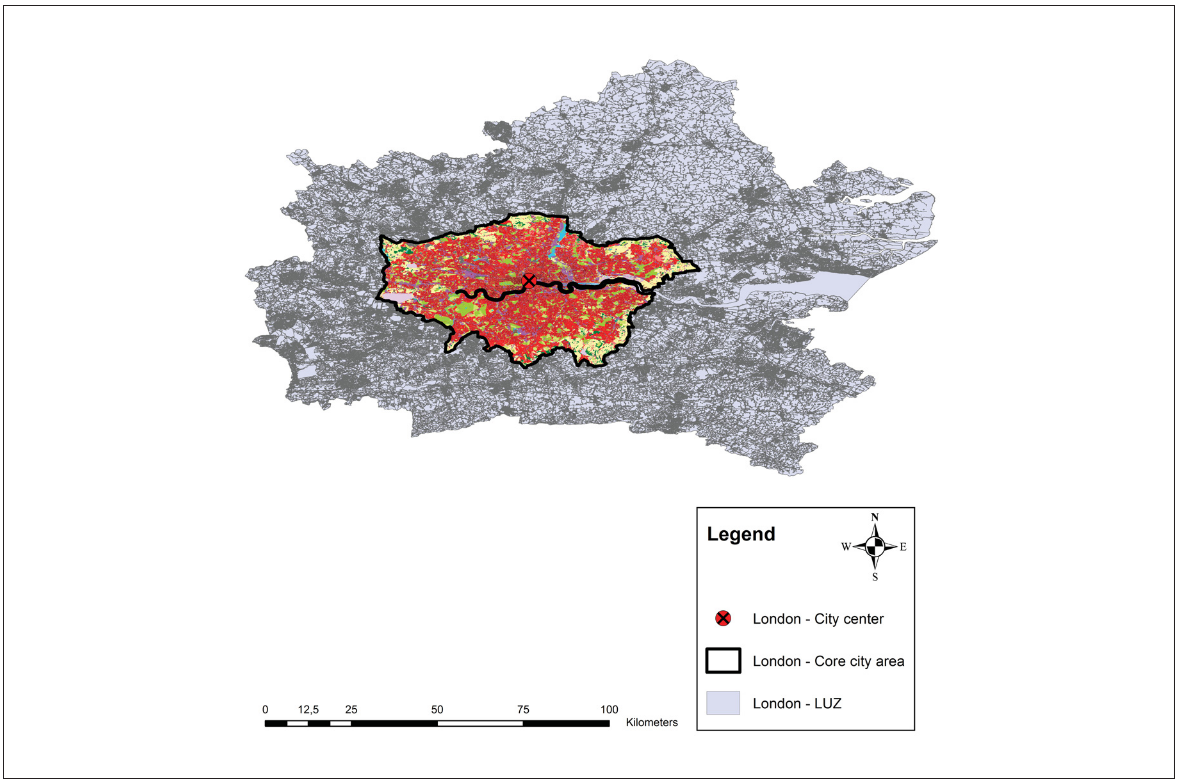


Figure I-2: Spatial differences between the administrative city borders (core cities) and the larger urban zones. Shown for London (UK)

I-5.2 Data

Investigating the main research hypotheses requires a three-dimensional set of data:

1. Uniform *GHG emission data* for each city.
2. Persistent *socioeconomic parameters* expected to affect urban GHG emissions.
3. Data that uniformly describes the *spatial urban properties* and LULC classes of all EU cities under investigation.

Because data quality is an important prerequisite for the presented analyses, the following Subsection presents an overview of the utilized datasets. More information about the specific data can be found in the individual Parts II, III, and IV that precisely describe the specific analyses that were required to analyze each research hypothesis.

I-5.2.1 GHG emission data

For analyzing urban GHG emissions, it is crucial that the analyzed GHG data cover the same emissions in all cities. Additionally, the spatial scope of the GHG emissions must be uniform across the cities.

The initial investigations revealed that a uniform set of GHG data was not yet available for EU cities, so a new database was developed that included comparable GHG data for 62 EU cities. Specifically, data were collected for all cities that covered CO_2-equivalents (**CO_2eq**) emissions that were modeled from the final energy uses of all scope 1 and 2 activities (Figure I-3). This methodology, in contrast to the consideration of direct emissions, presents a more applicable approach for small-scale territories like urban areas. For example, it enables the inclusion of energy and fuels consumed by urban dwellers which are produced outside a city's borders. Furthermore, upstream emissions for energy production were considered.

Using standardized GHG emission inventory models (e.g., ECOSPEED's widely used online software "ECORegion"[10]), these energy consumptions were then converted into CO_2eq emissions per capita[11]. When analyzing cities of different sizes, using the measure "GHG emissions per capita" is more appropriate than investigating a city's overall urban GHG emissions, which scale with its size. Furthermore, the reported GHG data also included corrections for cities' different climatic conditions to avoid climatic biases. Please note that in contrast to Figure I-3, only information about the CO_2eq emissions were collected, which represents the most important GHG (IPCC 2014).

In addition to direct data provisions from city administrations, who often used the ECORegion-tool for calculating their emissions for 2007-2009, data for UK cities came from AEA's technical report "Local and Regional Carbon Dioxide Emission Estimates for 2005-2009 for the UK" written for the Department of Energy and Climate Change (Webb et al., 2011). A list of all urban GHG data can be found in Part II.

For specifically investigating the influence of socioeconomic urban characteristics on transport GHG emissions, an extra "transport GHG emission dataset" was produced and analyzed. More information on this dataset can be found in Part II.

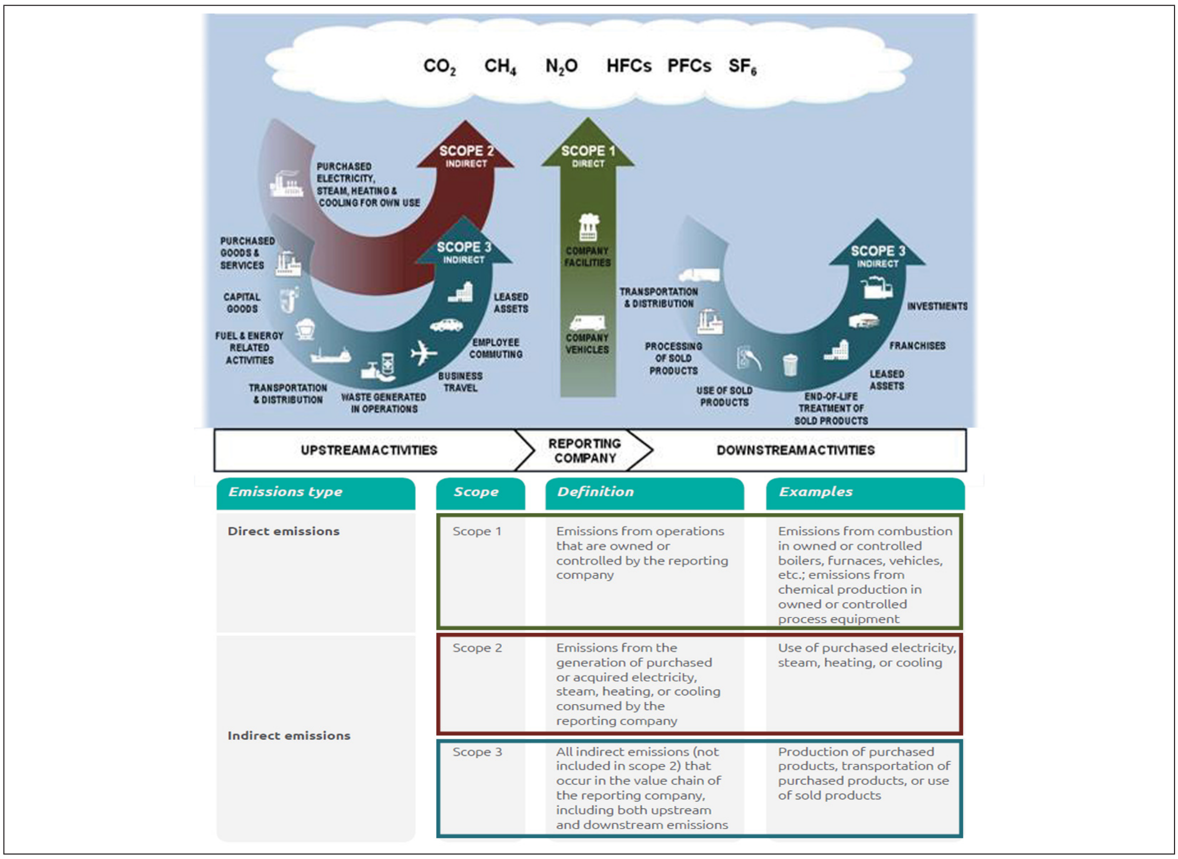
I-5.2.2 Socioeconomic data

A main research hypothesis is that the socioeconomics of a city's population affect its GHG emissions. In this context, there is already a broad body of scientific literature that finds certain socioeconomic indicators to correlate with urban GHG emissions per capita (Chapter I-2).

To re-investigate the most common assumptions about the possible impacts of socioeconomic urban characteristics of GHG emissions, specific socioeconomic data were collected and analyzed for all EU cities under investigation. The main data source was

[10] Is now called "ECOSPEED Region" (ECOSPEED AG, 2014). Because the software was called "ECORegion" until 2012 and renamed after the first publication of these results, it is referred to its original name throughout the entire thesis for consistency.

[11] Subsequently referred to as GHG emissions.



Emissions type	Scope	Definition	Examples
Direct emissions	Scope 1	Emissions from operations that are owned or controlled by the reporting company	Emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment
Indirect emissions	Scope 2	Emissions from the generation of purchased or acquired electricity, steam, heating, or cooling consumed by the reporting company	Use of purchased electricity, steam, heating, or cooling
	Scope 3	All indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions	Production of purchased products, transportation of purchased products, or use of sold products

Figure I-3: The scopes of GHG emissions. Figure shows the six gases that are defined as “greenhouse gases”, according to the UNFCCC , and their main direct and indirect anthropogenic drivers. Sources: Sjolander (2011); World Resources Institute and World Business Council for Sustainable Development (2011)

the EU Commission’s statistical data service Eurostat, which provides comprehensive and uniform statistical data for all EU countries, regions and cities (Eurostat, 2011a). These data were assessed for the period 2007-2009, and included information such as that from the UAT project. More detailed information about all analyzed socioeconomic parameters and their respective data sources are shown in Table 2 in Part II.

In addition to the main research activities, further analyses were conducted (e.g., analyzing GHG emissions from transport activities exclusively) to complement the general understanding of urban GHG emissions. Auxiliary information about the respective data needs and scientific methodologies are described alongside the particular research in Parts II-IV.

I-5.2.3 Spatial data

For analyzing possible influences of a city’s spatial urban characteristics on its GHG emissions (main research hypothesis II), spatial data were needed that uniformly describe the spatial layouts of all EU cities under investigation. The UA project by the EU

Commission's Directorate-General (**DG**) Enterprise Global Monitoring for Environment and Security bureau and DG Regional Policy was identified as a suitable data source, in that it included data for cities' LUZ and, more importantly for the presented research, the administrative areas (European Commission and Goulet, R., 2011). For compiling the UA dataset, various data sources were combined to develop high resolution digital LULC maps (image reference year: 2006 (+-1 year) of all EU cities with more than 100,000 inhabitants. Input data sources include inter alia multispectral or pan-sharpened earth observation data (2.5 m spatial resolution), topographic maps at a scale of 1:50,000 or larger, navigation data (for road network), and data for the detection of the degree of soil sealing. More precise information can be found in the UA "mapping guide" (European Environment Agency and Meirich, 2011).

The analyzed dataset contained information on 20 different LULC classes, covering built-up structures as well as natural areas. In contrast to socioeconomic information, uniform spatial data were only available for 52 of the 62 introduced EU cities (blue colored cities in Figure I-1). Reasons for this shifted coverage, which led to the exclusion of the ten cities (red colored in Figure I-1), include national affiliation. For example Swiss cities were not included in the UA but in the UAT.

Figure I-4 shows typical UA data examples and Chapter VI-2 in the Appendix presents more detailed descriptions of all included LULC classes. Further information about the analyzed spatial data is provided alongside the analyses of research hypotheses II and III (Part III and IV).

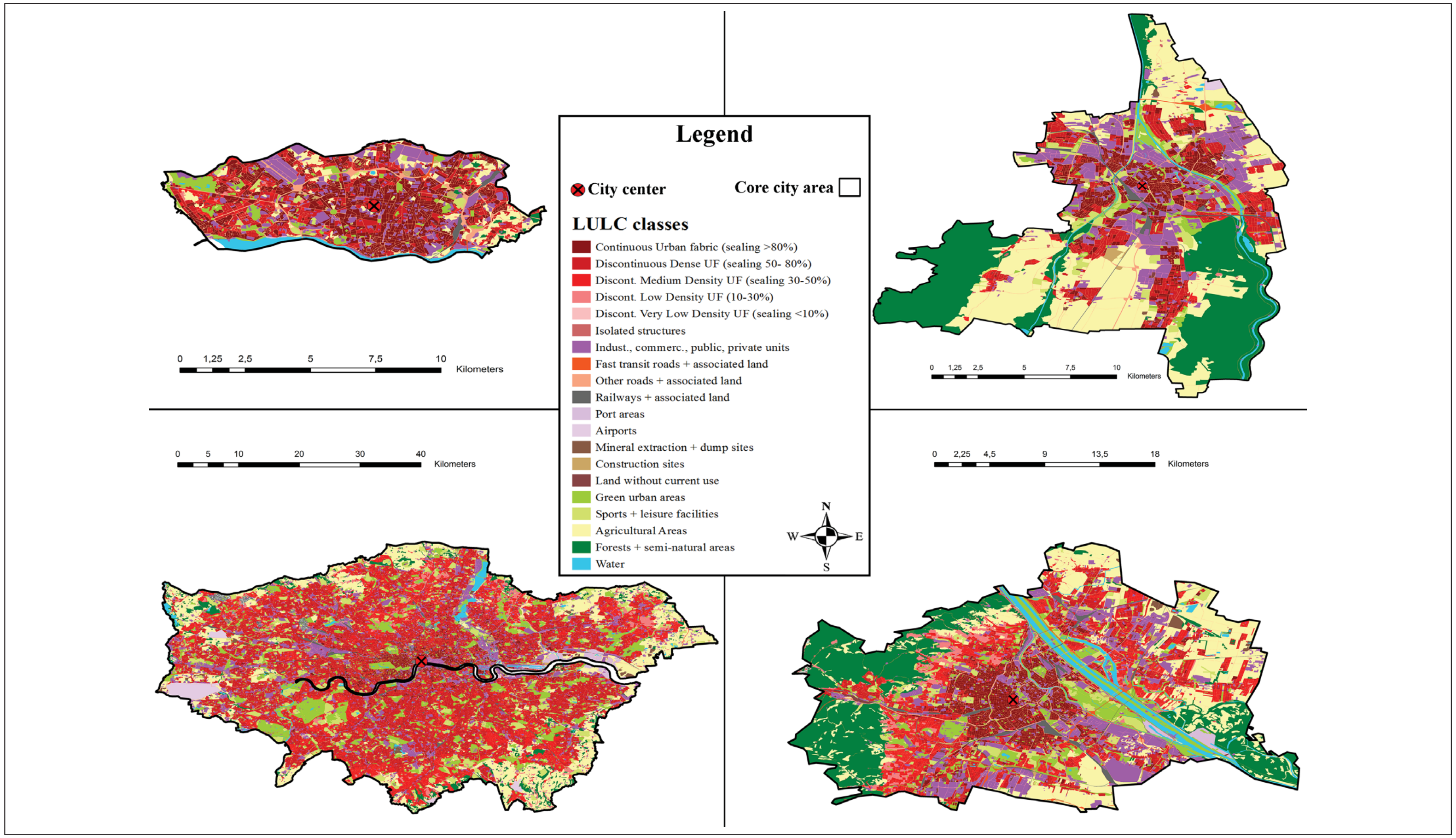


Figure I-4: Urban Atlas data examples (core cities with LULC information and calculated city centers). Examples, are shown for Porto (*medium-sized* city in Portugal) [**top left**]; Augsburg (*medium-sized* city in Germany) [**top right**]; London (*million* city in UK) [**bottom left**]; and Vienna (*million* city in Austria) [**bottom right**]. Scales vary to improve presentation. Further information about the different size classes are presented in Part II and details about all LULC classes can be found in Chapter VI-2

I-5.3 Methodologies

I-5.3.1 Determination of socioeconomic urban parameters

For analyzing research hypothesis I, specific socioeconomic data were needed for the cities under investigation. These urban characteristics are commonly assessed by city departments and collected by regional administrations (e.g., the EU Commissions' Eurostat). Therefore, analyzing the particular influence of the introduced socioeconomic parameters on urban GHG emissions hardly required any new data processing. Moreover, information could be collected from verified sources (Table 2 in Part III).

In order to validate existing assumptions about the influence of population density on urban transport GHG emissions (Part II), the statistical software "MATLAB" (MathWorks Deutschland, 2012) was used to process the "Emissions Database for Global Atmospheric Research- **EDGAR**" (European Commission, Joint Research Centre/ Netherlands Environmental Assessment Agency, 2009), as well as geospatial population density data from the "Gridded Population of the World- **GPW**" dataset (Balk et al., 2005). 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 respective urban area.

I-5.3.2 Determination of spatial urban parameters

In regard to the potential influence of urban spatial properties on the GHG emissions of a city (research hypothesis II) spatially explicit indicators were calculated utilizing the introduced high-resolution UA LULC data.

Considering relevant urban processes (Figure I-3), it proved to be useful to determine in particular two main parameter classes:

1. Urban structure indicators (incl. urban shape complexity).
2. Intra-urban LULC distributions and compositions.

In contrast to the socioeconomic parameters, the spatial indicators had to be compiled for all cities under investigations. Therefore, specific analysis processes were required, which are introduced in the subsequent paragraphs. As especially the urban center is of great importance for both parameter sets, a systematic approach to determine cities' central areas is also described. If not stated otherwise, the main software package used for the spatial parameter calculation was ArcGIS 10.1 (ESRI, 2012a). An overview of all analyzed spatial indicators can be found in Table 1 in Chapter III.

City Center

As described earlier (Chapter I-2) a city's central area is linked to important urban processes. Therefore, a systematic way of defining cities' central areas is crucial for the development of comparable spatial parameters. In particular, "intra-urban distance parameters" strongly depend on an accurate and uniform detection of the urban center.

For developing a suitable automated approach, the specific functions and spatial properties of the CBDs were considered (Chapter I-2). After investigating the definitions and descriptions of all UA LULC classes, it was found that the urban center is related to the UA LULC class "Continuous Urban Fabric" (**CUF**). Therefore, the median center of each city's CUF was calculated and defined as its city center. These areas were further used to derive information such as the intra-urban distance. In Figure I-5 the calculated city center of London is compared to information about the "real city center". This proves the suitability of the introduced calculation approach. The calculated urban centers for the cities of Vienna (Austria), Augsburg (Germany), and Porto (Portugal) are shown in Figure I-4, and the city centers of all other EU cities under investigations are graphically presented in Chapter VI-1 in the Appendix .

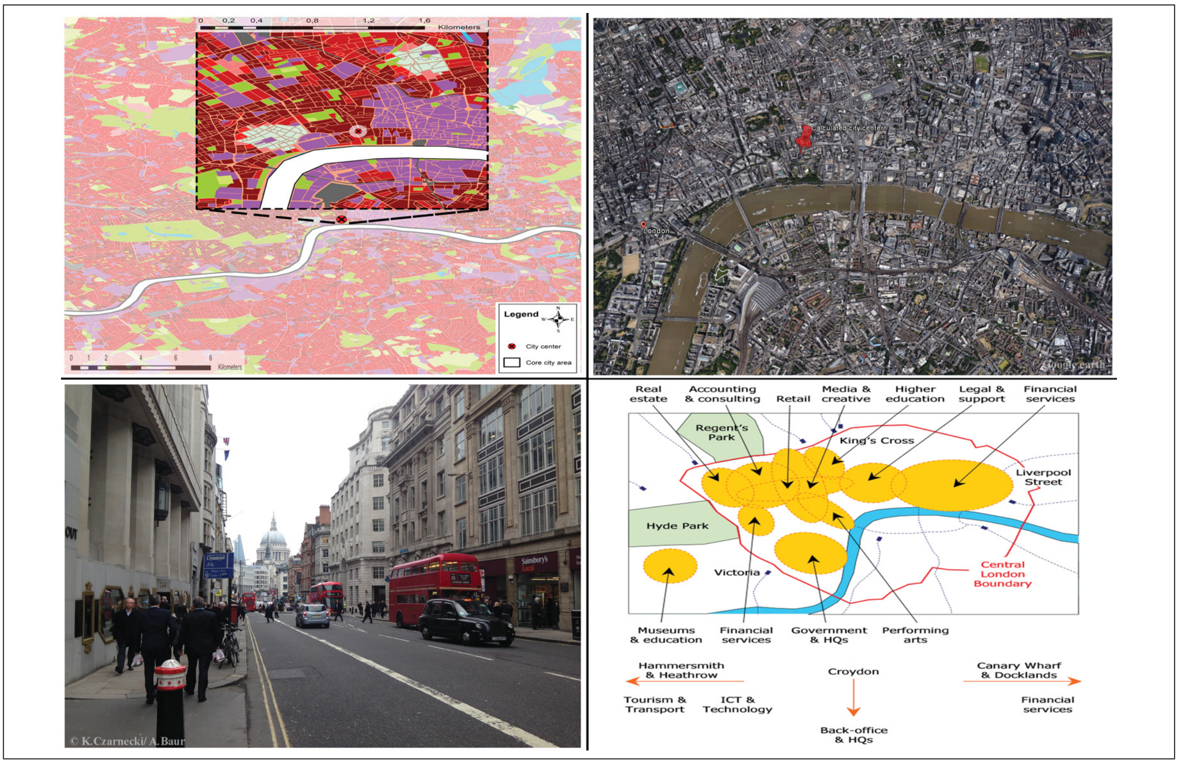


Figure I-5: Verification of the city center calculation. Example shown for London (UK).
UA data of central London incl. close-up to improve presentation of the calculated city center [**top left**]; Real situation presented by satellite imagery (incl. red indication of calculated city center) [**top right**], street foto taken at calculated position [**bottom left**], and description of local industries (Greater London Authority, 2008) [**bottom right**]

Urban structure indicators (incl. urban shape complexity)

For analyzing potential influences of the spatial urban layout on the GHG emissions of a city, eight indicators describing a city's structural properties[12] were calculated with the "Patch Analyst extension for ArcGIS" (Rempel et al., 2012) for the entire urban area as well as for all distinctive LULC classes. All indicators were shown to be relevant for investigating the urban layout (Part III). Afterwards, investigations of the city-specific LULC composition could be performed. In Figure I-6 a schematic flow chart summarizes the most important analysis steps.

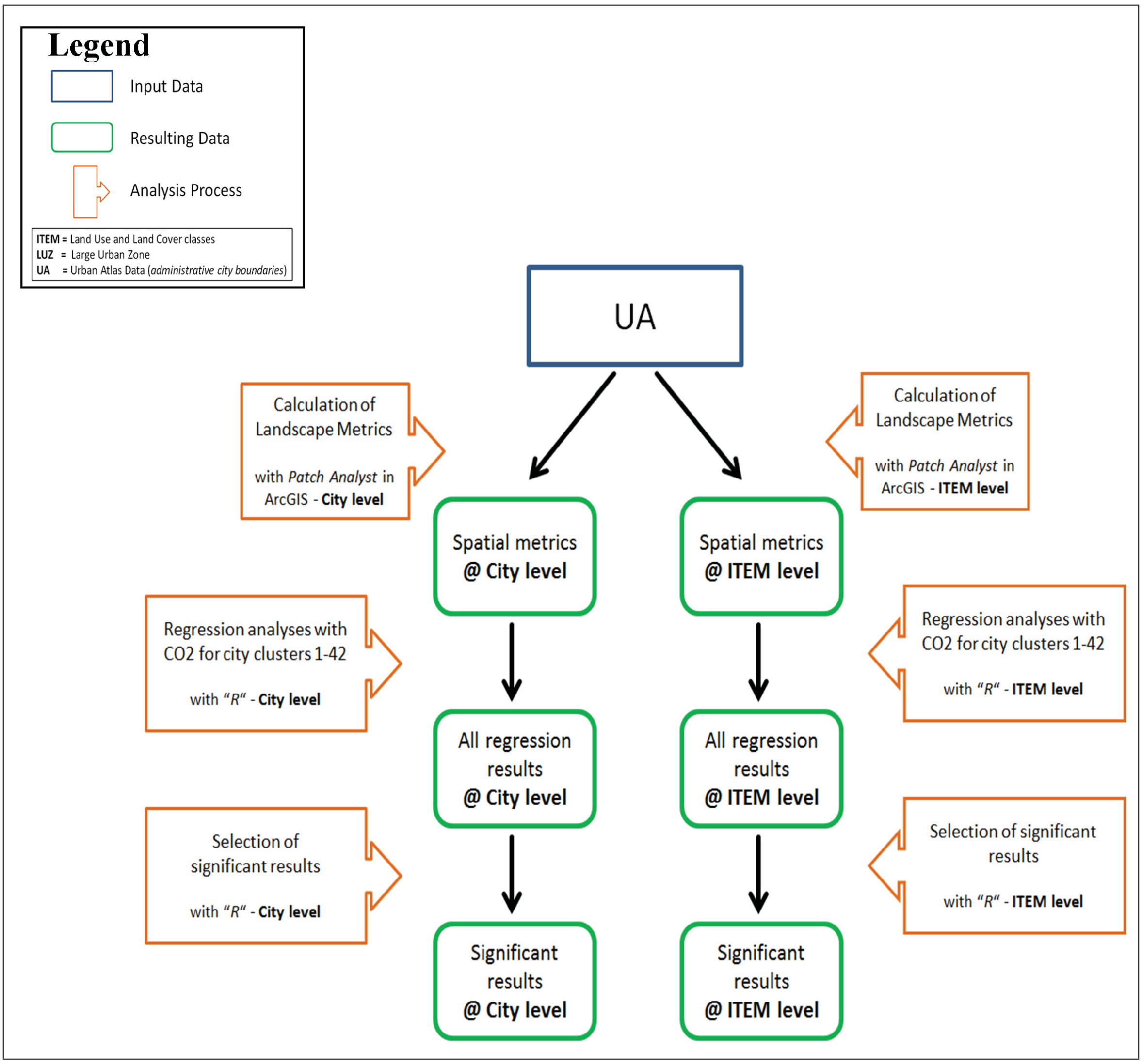


Figure I-6: Schematic illustration of the ArcGIS model for calculating the landscape metrics indicators incl. the regression analysis with urban GHG emissions

[12] Edge density, absolute and relative number of patches, mean patch edge, mean patch size, absolute and relative total area, and total edge. Further information can be found in Table 1 in Part III.

Urban Shape Complexity ($PUSH_C$)

For exploring, if the role of the overall urban shape relates to urban GHG emissions, an approach was developed to analyze the complexity of a city's overall shape (Figure I-7b). Therefore, the ArcGIS tool "Bounding containers" (Petterson, 2010) was used to calculate the smallest possible circle around each core city. Assuming that a larger difference between the area of the constructed circle and the actual urban area corresponds to a more complex, frayed urban outline, the $PUSH_C$ parameter (Algorithm I-1) was defined as a measure for urban shape complexity for all EU cities under investigation.

Algorithm I-1 Parameter of Urban Shape Complexity ($PUSH_C$) calculated using a constructed circle; with $PUSH_C$ between 0 (very complex urban growth) and 1 (perfect circular urban growth)

$$PUSH_C = \frac{Urban\,area\,[km^2]}{Area\,of\,constructed\,minimal\,circle\,[km^2]}$$

Intra-urban LULC distributions and compositions

To investigate the potential influence of intra-urban LULC distributions (related to the city center) and compositions on urban GHG emissions, particularly four indicators[13] were expected to deliver important insights. They were analyzed for all urban UA LULC classes using the ArcGIS function "Multiple Ring Buffer analysis" (ESRI, 2012b). This divided each city area into concentric circles around the previously derived city centers. To account for possible biases due to varying city sizes, distances from city centers were calculated in absolute (every 1km) as well as in relative terms (every 10% of the maximum urban radius). In Figure I-7a a schematic illustration of the ArcGIS model is shown and an example analysis of the relative distances of the LULC class (**DDUF**) is presented in Figure 1 in Part III for the city of London.

[13] Development of LULC classes across the city, LULC hotspots, LULC hotspot distances, and LULC maximum extents. Further information can be found in Table 1 in Part III.

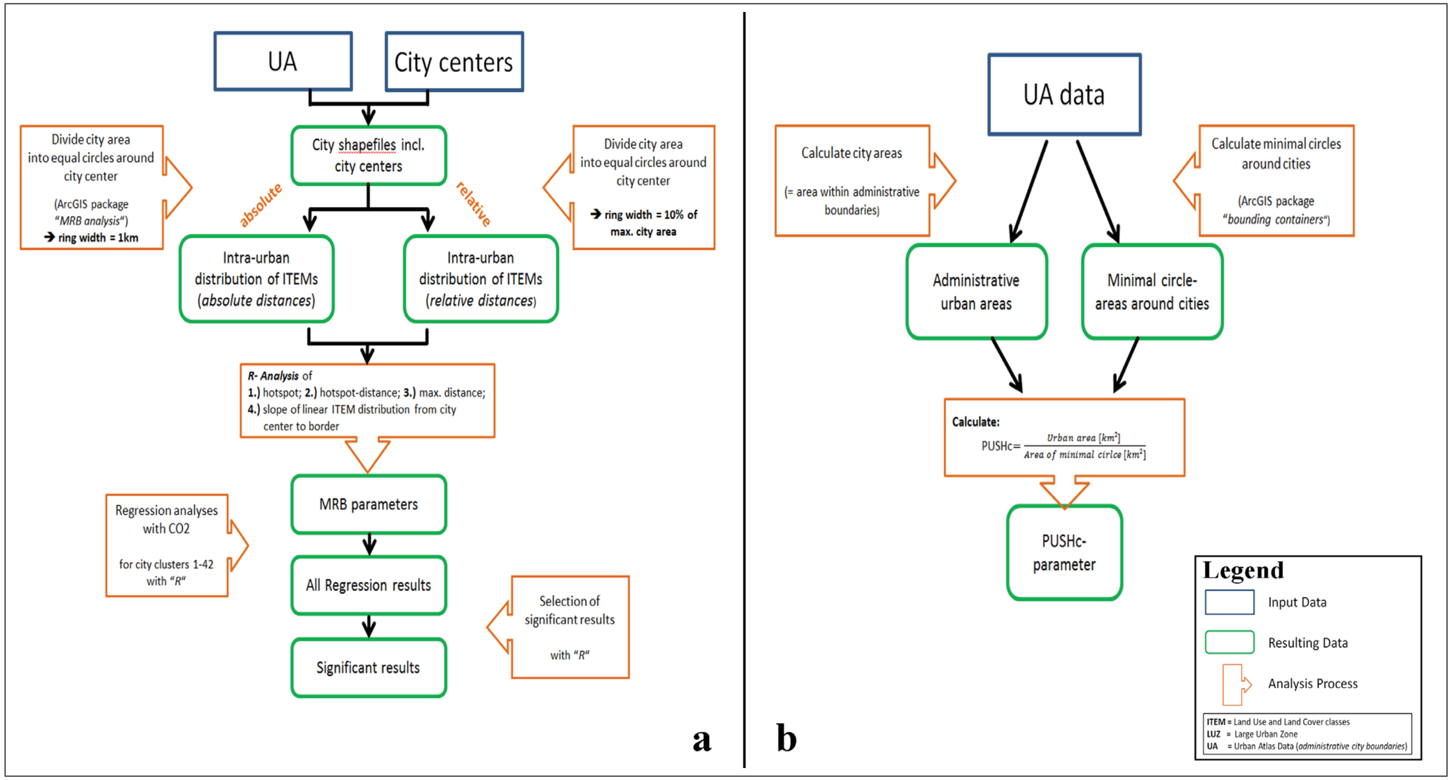


Figure I-7: Schematic illustration of the ArcGIS model for calculating LULC distributions [**a**] and the PUSHc parameter [**b**], incl. the regression analysis with urban GHG emissions

Harmonization of GHG emission data

As introduced previously (Chapter I-5.2.1), the total urban GHG emissions are mainly a product of transport, residential activities and energy generation. Whereas transport and residential activities are highly city-specific (and thus, the focus of this study), urban electricity generation is more strongly influenced by regional or even national developments (such as the installation of renewable energy sources). However, on this larger scale, there are significant differences in the GHG intensities of power generation between EU nations (Figure I-8). Therefore, emissions from the power generation present a possible uncertainty or even error when using EU-wide urban GHG data for investigating local socioeconomic and spatial GHG drivers.

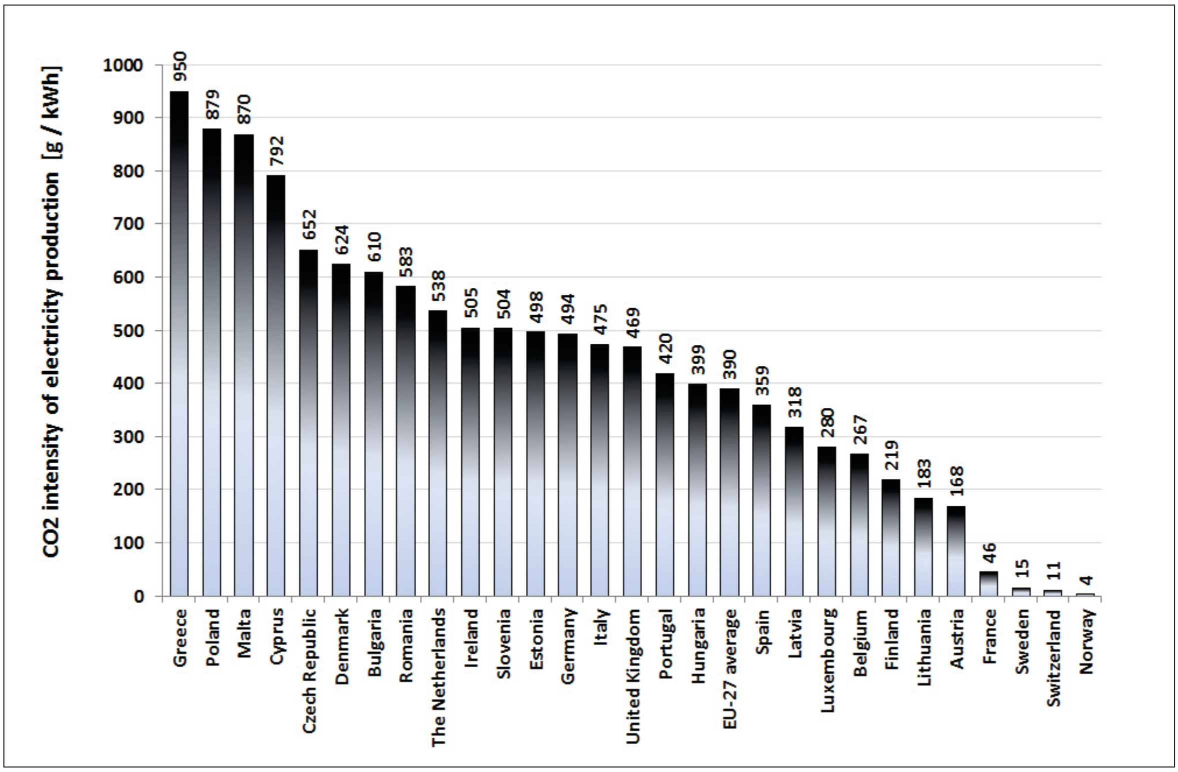


Figure I-8: Varying CO_2 intensities for electricity production in EU countries. Data from Oesterreichs Energie and Eurelectric (2012)

To account for this possible error, a simple correction approach was developed to level-out potential GHG biases caused by nation's varying electricity CO_2 intensities. Thus, it is assumed that in general 29.39% of the investigated urban GHG emissions are caused by power generation (The Shift Project, 2012). This share of each cities' GHG was corrected taking their national-specific electricity CO_2 intensity into account, which made the overall urban GHG emissions more comparable for all EU cities under investigation. The following equation summarizes this GHG correction method:

Algorithm I-2 GHG correction for nations' varying CO_2 intensity of electricity generation (**GHG_{rep}** = reported emission data from cities; **GHG_{cor}**= final corrected emission data)

$$GHG_{cor} = GHG_{rep} - 29.39\% \times GHG_{rep} + (29.39\% \times \frac{GHG\,rep}{CO_2\,elec.intensity})$$

The corrected GHG emissions[14] were then used throughout all presented analyses. A list of all cities including their corrected and their originally reported GHG emissions can be found in Table A.1 in Part IV.

A final goal was to not only investigate the most influential GHG drivers, but also to model EU urban GHG emissions. Thus, a correction factor ($\boldsymbol{\delta}$) was introduced, which represents the ratio between the corrected and the original GHG emissions (reported by cities). This factor is used to enable a comparison between the presented modeled GHG emissions (based on corrected emission data in Part IV) and the reported GHG emissions. Therefore, using δ enables the direct estimation of GHG emissions, without correcting for varying electricity CO_2 intensities (further information are provided in Chapter V-4.2).

I-5.3.3 Statistical analyses to determine significant drivers of urban GHG emissions

To investigate the specific influences of the aforementioned socioeconomic and spatial indicators on cities' total urban GHG emissions, statistical analyses were conducted. In this regard, bivariate and multiple regression models were developed to comprehensively identify the most important GHG determinants for the EU cities under investigation.

Bearing in mind that city departments should be able to analyze the potentially identified GHG drivers, linear models have been prioritized, as these are considered easier to use and interpret than non-linear models (Frost, 2011). To this end, certain non-linear relationships had to be transformed to be applicable in linear regressions. For example the assumed logarithmic influence of population density on the GHG emissions per capita (power law with exponent α) was "log-log-transformed" (into a straight line with slope α in a double logarithmic plot) to describe the same relationship in a linear dimension. Overall, cities' GHG emissions were analyzed, both in entirety as well as in 41 distinctive city clusters with specific urban properties (e.g., national affiliations, population sizes, or growth or decline patterns). Thus, it was also possible to account for specific urban peculiarities (e.g., of medium-sized cities or of fast-growing urban areas) that might influence a city's GHG emissions.

[14] Subsequently referred to as "GHG emissions" if not stated otherwise.

All statistical analyses were conducted using the open source statistic software package "R" (R Development Core Team, 2012). For gaining insights into the statistical significance of the investigated parameters and on the quality of the constructed models, the statistical measures "R^2" (informing about the quality of a found influence) and the F-statistics ("p-values"), showing the significance of a parameter's influence were calculated (Backhaus et al., 2010; Crawley, 2013). In particular with respect to the development of multiple regression models, statistical independence of possible emission drivers must be provided. Therefore, the Variance Inflation Factor (upper limit: 10) and the Durbin Watson test (lower limit: 1.5; upper limit: 2.5), were used to check potential determinants for multicollinearity and autocorrelation (Backhaus et al., 2010; Black and Babin, 2009; Reinboth, 2007). Finally, to identify a suitable multiple regression model (good statistical quality with reduced model complexity), the "Akaike's information criterion - **AIC**" (Crawley, 2013) was applied. If the identified model still included statistically insignificant influences, the variables' p-values were considered exclusively to focus on significant parameters (Backhaus et al 2010).

I-6 Research structure

For carrying out the described research, a cumulative research design was chosen (Figure I-9). Thus, after the main incentives, data and methodologies are introduced, three distinctive Parts are used to present research into urban GHG emissions in the EU, each according to one of the introduced research hypotheses.

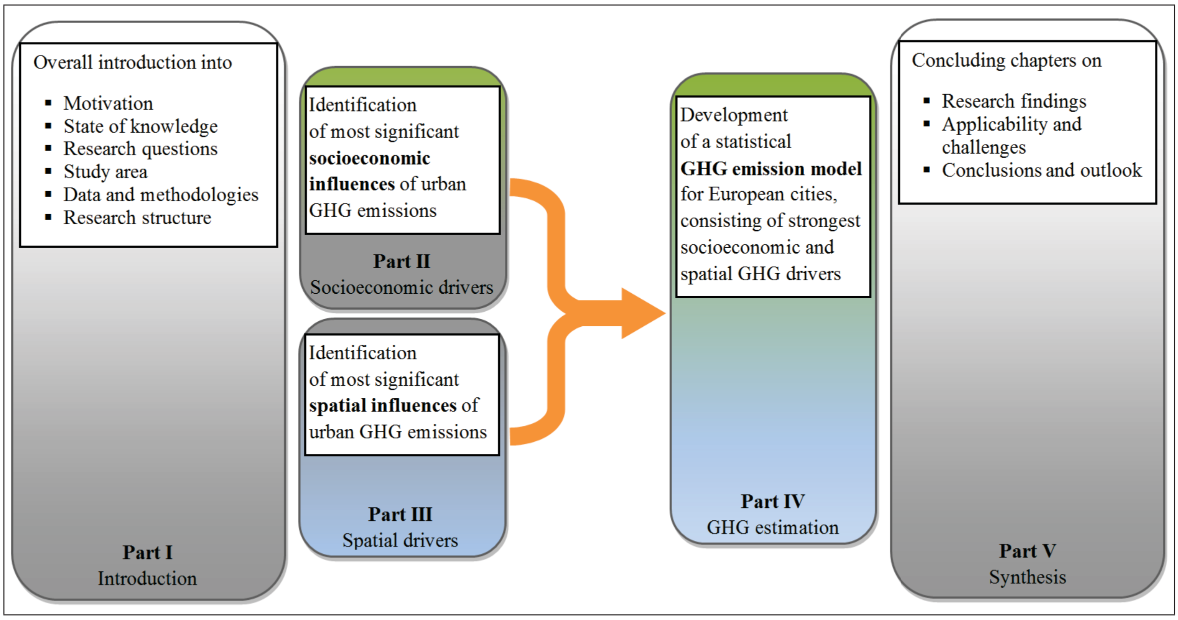


Figure I-9: Schematic illustration of the underlying research design

All three Parts (II to IV) have been published in relevant scientific journals:

- **Paper 1:** Baur A.H., Thess M., Kleinschmit B., Creutzig F. (2013): Urban climate change mitigation in Europe: Looking at and beyond the role of population density, *Journal of Urban Planning and Development*, doi:10.1061/(ASCE)UP.1943-5444.0000165

- **Paper 2:** Baur A.H., Förster M, Kleinschmit B. (2015): The Spatial Dimension of Urban Greenhouse Gas Emissions: Analyzing the influence of spatial structures and LULC patterns in European cities, *Landscape Ecology*, doi: 10.1007/s10980-015-0169-5

- **Paper 3:** Baur A.H., Lauf, S., Förster M, Kleinschmit B. (2015): Estimating greenhouse gas emissions of European cities- Modeling emissions with only one spatial and one socioeconomic variable, *Science of the Total Environment*, doi: 10.1016/j.scitotenv.2015.03.030

The respective papers are presented unchanged in this thesis (except for altered page numbering and headers) and a bilingual abstract is prepended to each manuscript to summarize the most important findings of each analysis. All Chapters jointly combine new-found knowledge to answer the overall research hypotheses and in the end develop a statistical model that can be used to estimate the GHG emissions of EU cities. A comprehensive discussion of all methodologies and findings, as well as clear recommendations for future research, form the last Part and thus, complete this thesis.

Part II

Research publication 1

Urban Climate Change Mitigation in Europe:

Looking at and beyond the Role of Population Density

Co-authors: Maximilian Thess, Dr. Birgit Kleinschmit, Dr. Felix Creutzig

Journal: Journal of Urban Planning and Development

Publisher: American Society Of Civil Engineers

Publication Date: 2013

Abstract

Motivation

Behavioral change in urban populations is increasingly important for climate change mitigation, including changes in transportation and other socioeconomic urban characteristics. These behaviors influencing GHG emissions should be affected by changing population densities.

Objectives and methodology

The importance of population density for climate change mitigation for EU cities is analyzed. Regression analyses are used to investigate its potential for reducing transportation energy demand and GHG emissions overall. Other potential socioeconomic GHG influences are also analyzed, which might help to reduce EU urbanites' emissions.

Results and conclusions

National GHG influences are found to also affect urban emissions. Thus, the spatial scale of analysis matters. Population density's role for emission reduction is uncertain for the whole EU, but confirmed for specific countries. Household size and personal wealth are determined to also be useful for this purpose in EU cities.

Zusammenfassung

Motivation

Die Bekämpfung des Klimawandels bedingt verstärkt Verhaltensänderungen der städtischen Bevölkerung. Die Wahl des Transportmittels, aber auch andere soziökonomische Eigenschaften spielen eine wichtige Rolle. Besonders die Populationsdichte wird als mögliches Mittel erachtet, um städtische Emissionen zu senken.

Ziele und Methodik

Es wird untersucht, ob Populationsdichteänderungen zur Reduktion von THG in EU Städten führen. Regressionsanalysen beleuchten einen möglichen Einfluss der Dichte auf den Energieverbrauch im Transportsektor und auf die städtischen Gesamtemissionen. Darüberhinaus werden weitere sozioökonomische Faktoren untersucht.

Resultate und Schlussfolgerungen

Resultate zeigen, dass sich nationale Emissionseinflüsse auch auf städtische Emissionen auswirken. Eine Beachtung der räumlichen Ebene ist daher wichtig für die Analyse urbaner Emissionen. Populationsdichte erscheint hierzu nicht als emissionsrelevant für eine EU-weite Analyse, jedoch für Untersuchungen auf nationaler Ebene. Auch die Haushaltsgröße und der persönliche Wohlstand beeinflussen städtische Emissionen in der EU.

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

Albert Hans Baur[1]; Maximilian Thess[2]; Birgit Kleinschmit[3]; and Felix Creutzig[4]

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.**

Author keywords: European cities; Climate change mitigation; Urban greenhouse gas emissions; Population density; Urban design.

Introduction

Although climate change has become a key issue of global policy-making (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 $2.5 \times 2.5°$; 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 ($\varnothing = 1.91$ PPH in these data) and comparably high GHG emissions per capita ($\varnothing = 9.89$ 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 ($\varnothing = 2.32$ 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

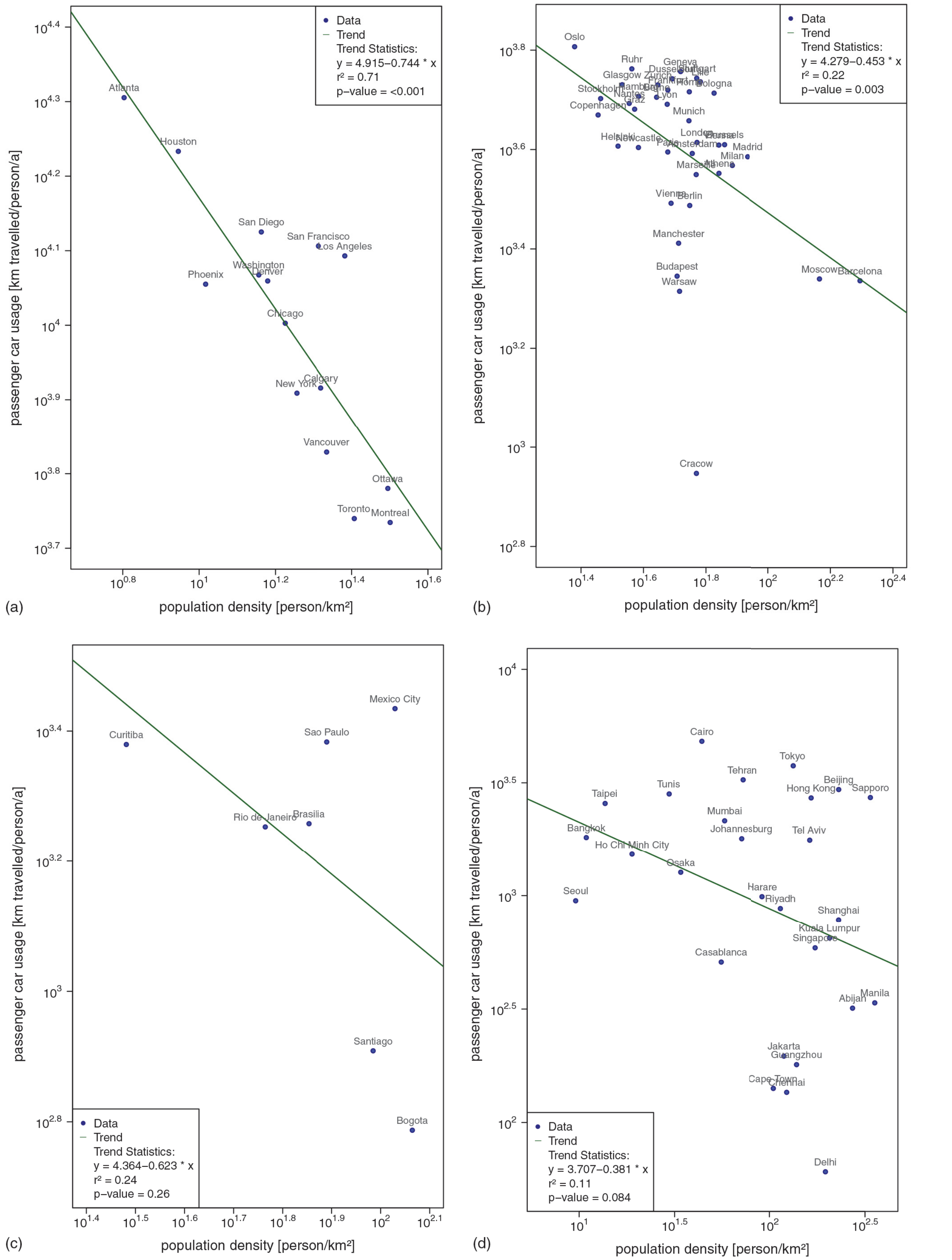

Fig. 1. Population density affecting gasoline consumption for various cities, shown as linear correlations in plots with logarithmic axes: (a) 15 North American cities; (b) 38 European cities; (c) seven South American cities; (d) 28 Asian cities [created from data from Kenworthy and Laube (1996)]

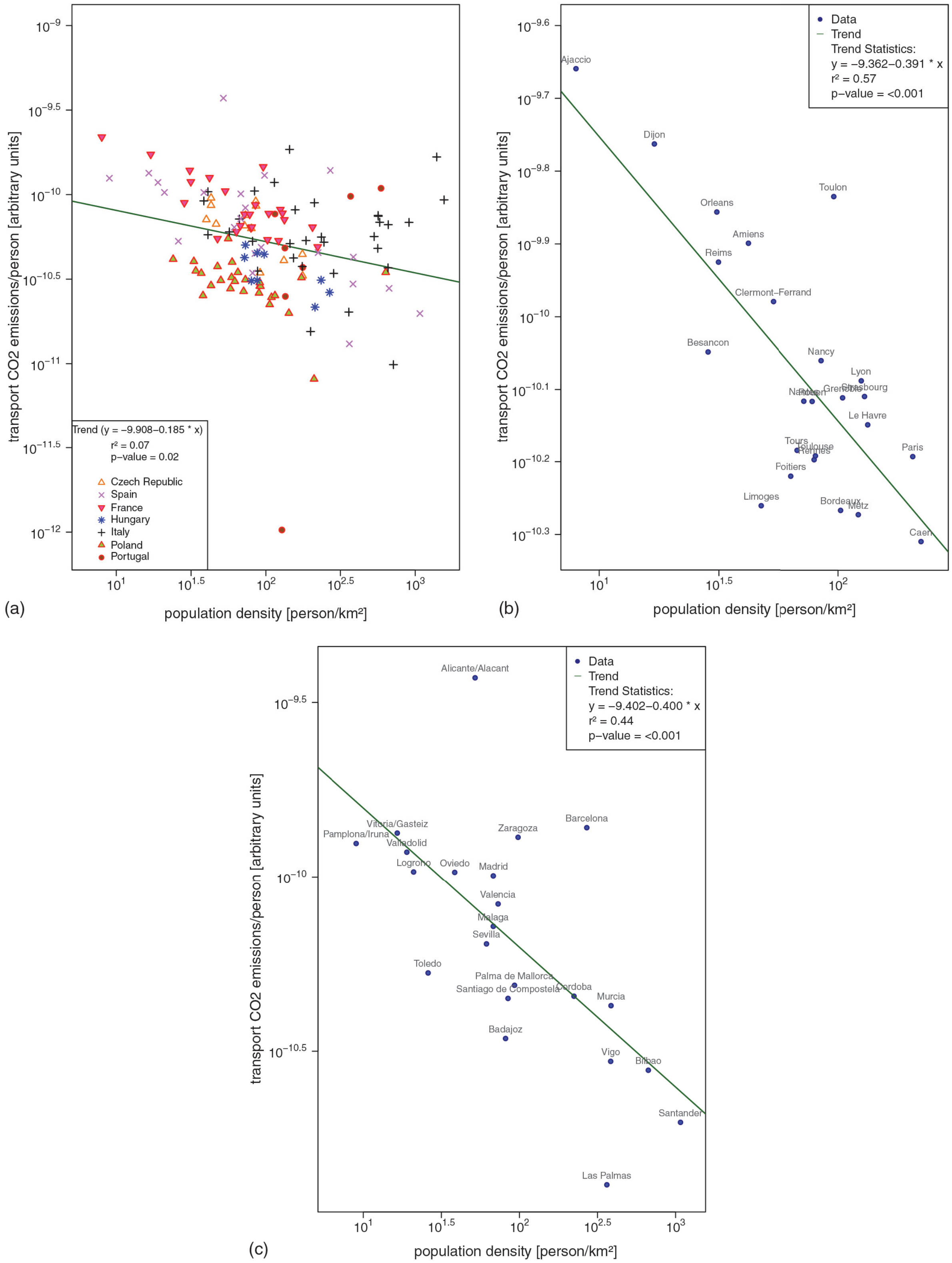

Fig. 2. Population density affecting CO_2 emissions from ground transportation for various cities; median data shown as linear correlations in plots with logarithmic axes: (a) 134 European cities; (b) 24 French cities; (c) 22 Spanish cities [created from data from Balk et al. (2005)9. European Commission,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

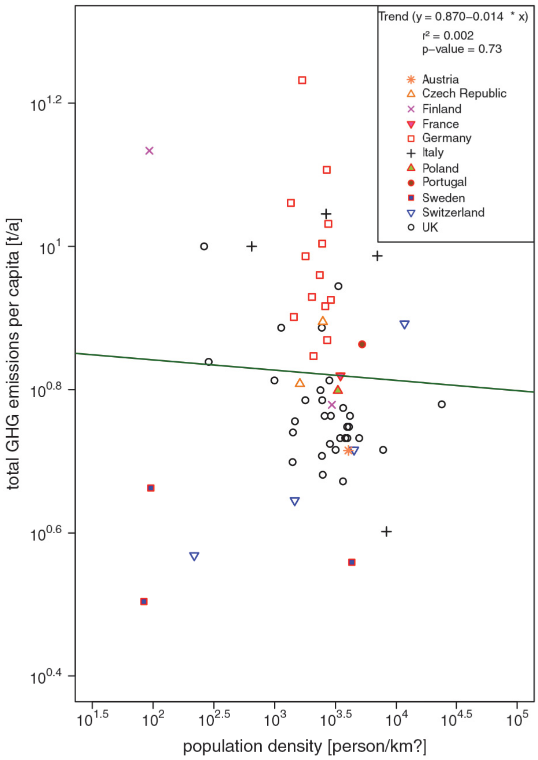

Fig. 3. Population density affecting urban GHG emissions for 62 European cities [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production), shown as linear correlation in a plot with logarithmic axes; a list of the analyzed cities is provided in Table 1]

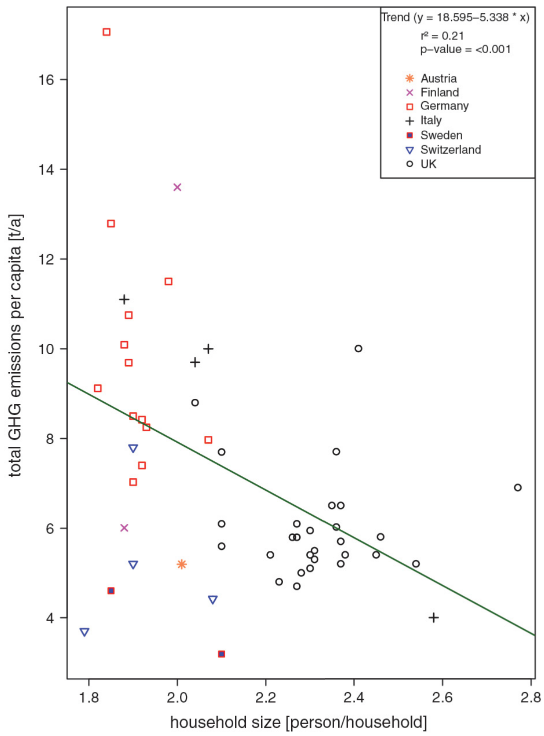

Fig. 4. Household size affecting urban GHG emissions for 54 European cities [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production); household size refers to the number of people living in one household; a list of the analyzed cities is provided in Table 1]

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

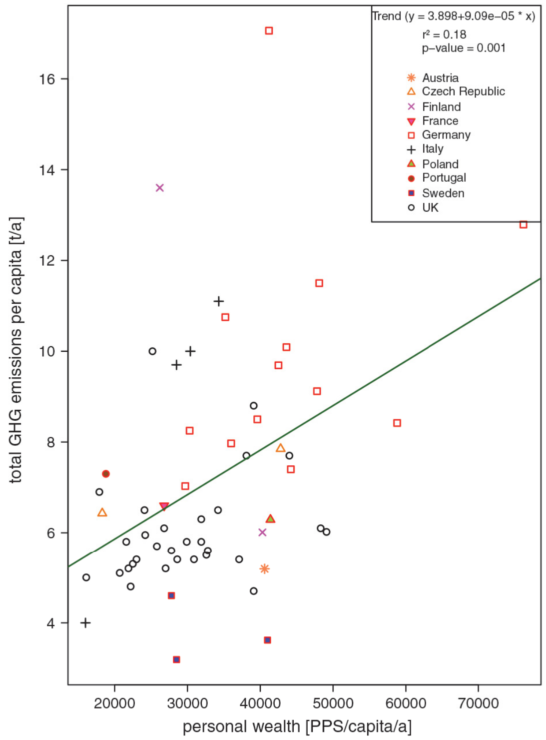

Fig. 5. Personal wealth affecting urban GHG emissions for 58 European cities [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production); personal wealth is reflected by information about PPS; a list of the analyzed cities is provided in Table 1]

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

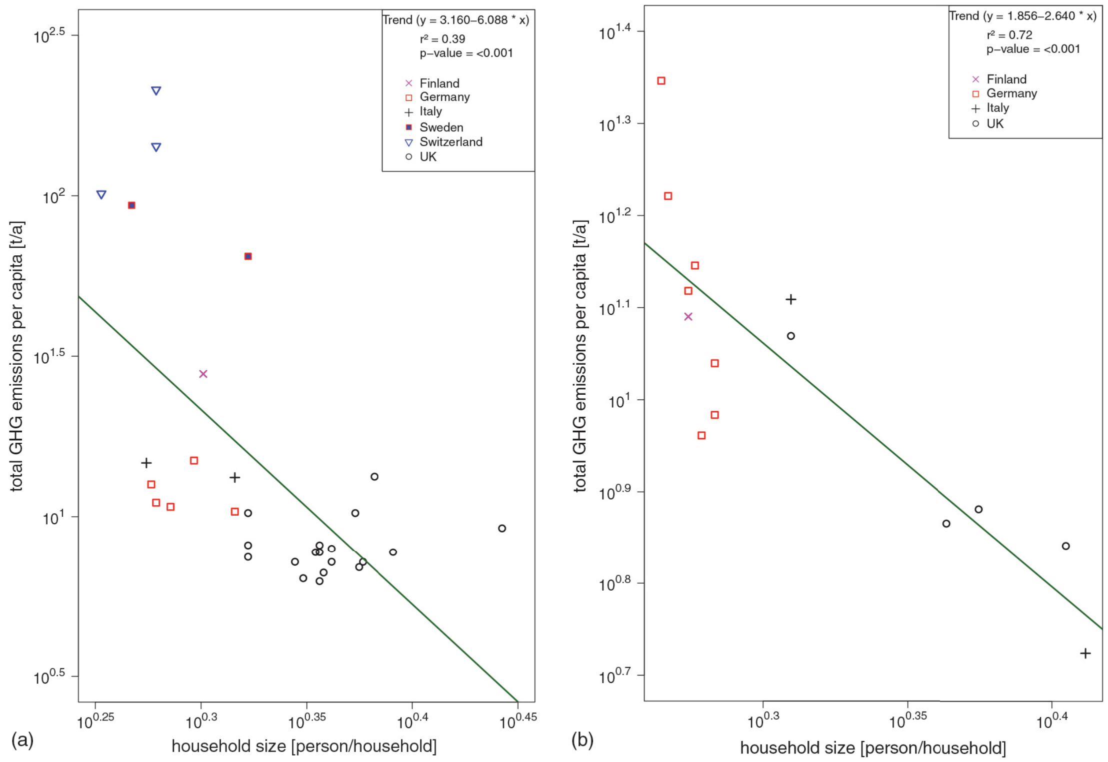

Fig. 6. Household size affecting urban GHG emissions for: (a) 31 medium-sized European cities; (b) 14 large European cities; [GHG data present Scope 2 GHG emissions (including upstream emissions for electricity production) and assume similar CO_2 intensities of electricity production; household size 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

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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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Part III

Research publication 2

The Spatial Dimension of Urban Greenhouse Gas Emissions:

Analyzing the influence of spatial structures and LULC patterns in European cities

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Abstract

Motivation

While previous analyses have identified socioeconomic influences on urban GHG emissions, information about the role of spatial urban structures and LULC patterns for climate change mitigation is sparse.

Objectives and methodology

This study analyzes the linkages between the spatial structure and LULC patterns of a city and its GHG emissions. Therefore, spatial and statistical analyses are used to investigate data from European Union's "Urban Atlas" for 52 European cities.

Results and conclusions

In particular, high amounts of sparsity in the urban fabric within large distances to the city center relate to increased urban GHG emissions. In contrast, fragmented, dense urban areas correlate with lower emissions. Overall, links between spatial urban properties and LULC compositions, and cities' GHG emissions are revealed, and urban sprawl is also recognized to increase cities' climate impact. Future research should consider these spatial urban emission drivers to help cities realize their climate change mitigation potential.

Zusammenfassung

Motivation

Während Studien bereits sozioökonomische Einflüsse auf städtische THG Emissionen identifiziert haben, gibt es noch wenig Wissen über den Zusammenhang zwischen räumlichen Stadtstrukturen, Landnutzung und -bedeckung (**LULC**) und urbanen THG Emissionen.

Ziele und Methodik

Daher untersucht diese Studie mögliche Zusammenhänge zwischen räumlichen Stadteigenschaften und LULC Mustern und urbanen THG Emissionen. Hierzu werden Daten des EU Projektes „Urban Atlas“ räumlich und statistisch für 52 EU Städte untersucht.

Resultate und Schlussfolgerungen

Speziell eine Vielzahl dünn besiedelter Areale, weit entfernt vom Stadtzentrum, steht im Zusammenhang mit höheren THG Emissionen. Im Gegensatz führen dichte, eher klein arealige Stadtstrukturen zu niedrigeren Emissionen. Im Großen und Ganzen wird so auch die negative Auswirkung von „urban sprawl“ auf den städtischen Klimaeinfluss deutlich. Zukünftige Forschung sollte diese räumlichen Emissionseinflüsse auf die urbanen Emissionen beachten und Städten so dabei helfen, ihre Potenziale zur Klimawandelbekämpfung zu realisieren.

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RESEARCH ARTICLE

The spatial dimension of urban greenhouse gas emissions: analyzing the influence of spatial structures and LULC patterns in European cities

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Abstract

Context Integrative mitigation and adaptation strategies are needed to counter climate change. Indicators can be valuable that focus on the specific relevance of cities' socioeconomic and spatial properties. While previous analyses have identified socioeconomic influences on urban greenhouse gas emissions, information about the role of spatial urban structures and land use and land cover patterns is sparse.

Objective This study advances the use of spatial metrics for analyzing the linkages between the spatial properties of a city and its greenhouse gas emissions.

Methods The relationship between nine types of spatial structure, four land use and land cover-based indicators, and the emissions of 52 European cities is investigated by spatially and statistically analyzing high resolution data from European Union's "Urban Atlas".

Results Spatial determinants of urban greenhouse gas emissions are identified, indicating a strong connection between urban sprawl and increasing emissions. In particular, high amounts of sparsity in the urban fabric within large distances to the city center relate to increased per capita emissions. Thus, a 10 % reduction of very low density urban fabrics is correlated with 9 % fewer emissions per capita. In contrast, high amounts of fragmented, dense urban patches relate with lower emissions.

Conclusions This study links urban spatial properties and land use and land cover compositions to greenhouse gas emissions and advances the understanding of urban sprawl. Future research needs to combine knowledge about socioeconomic drivers with information about the identified spatial influences of urban greenhouse gas emissions to help cities realize their climate change mitigation potential.

Keywords Climate change mitigation · Urban design · Landscape metrics · Urban form · Urban shape · Urban planning

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Introduction

Climate change is one of the most pressing challenges of the 21st century. The need to both mitigate greenhouse gas (GHG) emissions as well as adapt to extraordinary weather phenomena caused by already changing climatic conditions is crucial (Halsnæs and Verhagen 2007; Guariguata et al. 2008; IPCC 2014),

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in particular for cities (Coutts et al. 2010; European Environment Agency 2012).

With more than 53 % of the human population living in urban areas (The World Bank Group 2014), cities are also responsible for the majority of global GHG emissions. Coherent insights on the main influences of urban GHG emissions are becoming increasingly important in reaching cities' potential for effective climate change mitigation strategies (Rickwood et al. 2008; Bergeron and Strachan 2011; Hoornweg et al. 2011; United Nations Human Settlement Programme 2011).

Previous research mainly focused on socioeconomic influences, finding that personal wealth, population density, household size, and heating or cooling requirements particularly affect urban GHG emissions per capita (Newman and Kenworthy 1989; Zhang et al. 2010; Heinonen et al. 2011; European Environment Agency 2012; Baur et al. 2013). Furthermore, challenges of urban sprawl were shown through the example of US cities (El Nasser and Overberg 2001; Ewing et al. 2007; Schneider and Woodcock 2008), European cities (European Environment Agency 2006; RWI et al. 2010), Chinese cities (Deng and Huang 2004; Feng and Li 2012), and other regions (Schneider and Woodcock 2008).

Although several studies have conducted analyses on the urban form or investigated extensively large sets of landscape metrics (Huang et al. 2007; Schwarz 2010), explicit analyses of the influence of urban spatial characteristics and specific land use and land cover (LULC) compositions on the GHG emissions per capita are still missing. However, as such investigations are considered important for a comprehensive understanding of a city's climate impact and for validating current knowledge about urban GHG emissions drivers (Makido et al. 2012; Liao et al. 2013), this research aims at analyzing the linkages between cities' spatial structures and urban GHG emissions.

In this context, by analyzing population density, urban compactness was found to be linked to decreasing per capita GHG emissions (Newman and Kenworthy 2006; Kennedy et al. 2009). As the density of a city's built-up structure is related to its city center as a key point for urban growth as well as for transportation dynamics, so called "Central Business Districts" (CBDs) are considered important for urban citizens' daily lives (Hartshorn 1992). Despite the fact that "edge cities" have begun to form alternate focal points in younger cities, CBDs are still mostly in central urban areas, concentrating monetary, cultural, and social values (Taubenböck et al. 2013; Rosenberg 2014; Wang et al. 2014). Thus, they are an attraction for a large share of daily commuters (Spiekermann 1997; Maciag 2014), and a possible influence on per capita emissions, in respect to distance from the CBD (Rickwood et al. 2008; Creutzig et al. 2012). From the LULC point of view, such areas are typically characterized by a high percentage of impervious dense urban fabrics.

Although the density of the urban fabric and the distances from the CBD might play a role in explaining the emissions of a city, this does not account for the possible relevance of its inner urban structure. A city might, for instance, be compactly structured, providing all services to its inhabitants at short distances and thus reducing overall GHG emissions. Therefore, also analyzing urban LULC compositions is important. As they have been shown to be relevant for analyzing the urban layout, in particular the edge density, the mean patch size, the total number of patches, the total edge, and the mean patch edge, according to previous research from Huang et al. (2007) and Schwarz (2010), should be included in investigations of possible linkages between urban LULC composition and GHG emissions per capita.

The following hypotheses are investigated in order to profoundly analyze the influence of spatial urban characteristics on the urban GHG emissions of European cities:

- Spatial urban density particularly influences GHG emissions per capita.
- The distances of various LULC classes to the city center affect GHG emissions per capita.
- In relation to urban structure, spatial metrics of urban patches (such as the edge density or the mean patch size) can provide evidence for varying GHG emissions. Thus, they can be utilized for showing that the specific composition of the LULC classes affects GHG emissions per capita.

Considering a city's specific situation (geographic location, city size, and growing or shrinking patterns), the presented hypotheses are tested by spatially and statistically analyzing urban GHG emissions per capita and high resolution LULC data from the European Union's "Urban Atlas" (UA).

Data

Analyzed cities

This study investigated the relation between structure and GHG emissions for 52 European cities that differ in terms of their specific urban properties (city and population size, geographical location, national affiliation, and urban growth or decline patterns—Table A1 in Online Appendix).

In terms of population, small (1 to 100,000 inhabitants), medium (100,001–500,000 inhabitants), large (500,001–1,000,000 inhabitants), and million cities (>1,000,000 inhabitants) were analyzed. With regard to their geographical location, cities were clustered in South-European and North-European, defined by Antrop (2004) as south of 46° longitude and north of 46° longitude, respectively. Additionally, cities' varying growth rates were considered, distinguishing fast growing urban areas (>1.01 % annual population growth) from slower growing urban areas (0.01–1.0 % annual population growth), and shrinking cities (<0.00 % annual population growth).

GHG emission data

Although international standards for GHG inventorying are currently being developed (Bhatia and Ranganathan 2004; UNFCCC 2007; C40 Cities 2012), urban GHG inventories often vary strongly (Hoornweg et al. 2011). Thus, we developed our own emission dataset (Baur et al. 2013) by combining comparable GHG information per capita for 62 European cities, considering urban scope 1 and 2 CO_2eq emissions (Bhatia and Ranganathan 2004). This includes emissions from both residential as well as non-residential sources. These data were reported by city administrators and were mostly calculated with the online tool "Ecoregion" (ECOSPEED AG 2012) for 2007–2009. Additionally, upstream emissions for energy production and corrections for seasonal variations were considered. Using information about the varying CO_2 intensities of the national energy mixes, further data correction was performed to account for nations' varying energy production methods.

Spatial data about LULC

Data from the UA project by the European Commission's *Directorate-General* (DG) *Enterprise Global Monitoring for Environment and Security* bureau and *DG Regional Policy* were used to assess the spatial properties of the cities under investigation. The UA project was set up to "[…] create harmonized maps of […] cities and their surroundings in the European Union" (European Commission et al. 2011). The dataset contains information on 20 different LULC classes, following the *CORINE Land Cover* nomenclature (European Environment Agency 1995). It covers both built-up areas as well as non-built up areas, such as parks and forests (SIRS 2011). The existing dataset includes 305 major agglomerations, defined according to Urban Audit's "Larger Urban Zones" at a geographical scale of 1:10,000. The image reference year was 2006 (±1 year). Although this acquisition date does not completely coincide with the analyzed GHG data, it is considered useful for the presented study, as extensive changes in the overall urban layout are not expected within the maximum offset time of 5 years.

Methodology

For analyzing the particular relevance of the LULC composition on a city's GHG emissions, nine indicators describing a city's structural properties (*urban structure indicators,* e.g., edge density, number of patches) were calculated for the entire urban area and for specific LULC classes, including information about the overall shape of the urban area. Additionally, four indicators regarding the specific distributions of various LULC classes within a city (e.g., a LULC classes' hotspot) were analyzed to validate the potential influence of intra-urban distances to the city center (Table 1). The latter indicators were obtained from the UA data using the software ArcGIS 10.1 (ESRI 2012). All statistical analyses were performed with the open source statistical software package "R"(R Development Core Team 2012). Overall, cities were analyzed both in entirety as well as in distinct clusters of cities with specific urban properties (e.g., national affiliations, population sizes, or growth or decline patterns).

Table 1 Information about all analyzed urban structure and LULC-based indicators (*ordered alphabetically*)

Name	Abbreviation	Information	Calculation focus
Development of LULC classes across the city	Development of trend	A linear trend of each LULC class is modelled. Its coefficients indicate increasing or decreasing developments of the LULC class from the city center to city border	Each LULC class
Edge density	ED	ED accounts for the total edge length relative to the total urban area.	Entire city
		Higher ED values indicate more fragmented patches	Each LULC class
LULC hotspots	Hotspot	Maximum relative amount of a LULC class in a certain distance from the city center (% of all LULC area/distance)	Each LULC class
Hotspot distances	Hotspot distance	Specific distance between the hotspot and the city center (m)	Each LULC class
LULC maximum extent	Max. distance	The maximum spatial extent of every LULC class from the city center. Calculated in absolute (every 1 km) and in relative (every 10 % of specific city size) terms (m)	Each LULC class
Mean patch size	MPS	MPS indicates the average size of the urban patches [km^2]	Entire city
			Each LULC class
Mean patch edge	MPE	MPE indicates the average edge length of the urban patches. It is calculated from the TE and NumP and describes the overall fragmentation of the urban area (km)	Entire city Each LULC class
Number of patches	NumP	Total number of patches within a city	Entire city
		NumP is used for various indicators, e.g., representing size or compactness	Each LULC class
Relative number of patches	NumP/km^2	NumP/km^2 equals the average NumP It is calculated from NumP and the entire urban area	Each LULC class
Relative total area	CA_PER	CA_PER represents the CA of a LULC class, but relative to the specific city size (%)	Each LULC class
Total area	CA	CA represents the size of the area of a LULC class or, if applied to the entire urban area, the city size (km^2)	Entire city Each LULC class
Total edge	TE	Total edge length of all urban patches. TE is often used for indicators that inform about the complexity of urban patches (km)	Entire city Each LULC class
Urban shape complexity	$PUSH_C$	$PUSH_C$ shows the deviation of a city's shape (urban area) from a perfect minimal circle. Thus, it indicates its shape complexity [0,1]	Entire city

Urban density

For analyzing the role of urban density for GHG emissions, we focused on the LULC classes "discontinuous very low density urban fabrics" and "discontinuous dense urban fabrics" because these classes are considered the most important in relation to urban dwellers' daily activities. Discontinuous dense urban fabric is described by a very high degree of soil sealing (>50–80 %, soil sealing equals the proportion of artificial areas compared to vegetated areas) and covers residential buildings, roads and other artificially surfaced areas. Discontinuous very low density urban fabrics show a low degree of soil sealing (<10 %) and contain mostly vegetated areas that are not dedicated to forestry or agriculture. This LULC class describes, for example, exclusive residential areas with large gardens. To analyze the role of urban density, the number of patches/km^2 (NumP/km^2) were calculated for both density classes.

Intra-urban distributions and distances to the city center

To determine whether intra-urban distributions and specific distances to the CBD for each of the 20 UA LULC classes relate to urban GHG emissions per capita, the following indicators were considered:

1. *Max. distance* the maximum spatial extent of every LULC class from the city center (in m).
2. *Hotspot* the maximum amount of each LULC class in a certain distance from the city center and in relation to all other LULC classes in this distance (in % of all LULC area).
3. *Hotspot distance* the specific distance between this hotspot and the city center.
4. *Development of trend* the linear development of each LULC class across the entire city.

In order to derive these indicators, an easily transferable approach to automatically determine the CBD of each city (subsequently referred to as *city center*) was developed. Considering its characteristic features, and according to the methodology of the UA data classification (European Environment Agency and Meirich 2011), the CBD was identified as the median center of the LULC class "Continuous urban fabric" (CUF) in each city.

Afterwards, the cities were partitioned using concentric circles with specific radial distances from the calculated city centers. Thus, the percentage of each specific LULC area at each distance across the urban landscape could be determined. This method was also useful in analyzing how the different LULC classes developed within the city (e.g., spreading from the city center towards the city border). Due to the possible scale effects caused by different city sizes, analyses were conducted using relative distances (10 % of the maximum distance between the respective city center and the city border). Figure 1 provides an example for the LULC class *discontinuous dense urban fabric* for the city of London.

LULC composition

To spatially analyze the effects of LULC composition on urban GHG emissions, the following landscape metrics were investigated for their influence on European per capita urban GHG emissions: (1) edge density (ED), (2) mean patch size (MPS), (3) number of patches (NumP), (4) total edge (TE), and (5) mean patch edge (MPE). Also, the (6) NumP/km^2 were calculated to account for possible biases caused by varying city sizes. All metrics were derived using the "Patch Analyst extension for ArcGIS (vers. 5.1)" (Rempel et al. 2012) for the entire city area, as well as for each of the available 20 LULC classes. Additionally, the entire area of each city (CA) as well as each of its LULC classes was considered. For the LULC classes, this was further calculated in relation to the specific city size (CA_PER), to detect both the absolute and relative occurrence of each of the 20 LULC classes in the cities. Because the landscape metric *TE* was highly correlated to all other metrics, it was excluded from further LULC-specific investigations.

Results and discussion

Urban density

When analyzing different LULC classes for their relation to GHG emissions, classes that represent the density levels of discontinuous urban fabric are found to be specifically related to urban GHG emissions per capita in the analyzed cities. In particular, the average number of patches (*NumP/km*^{2}) of *discontinuous very low density urban fabric* (Fig. 2) and of *discontinuous dense urban fabric* correlate with emissions per capita.

As shown in Fig. 2, a higher average amount of patches with very low density urban fabric (<10 % average degree of soil sealing) indicates higher GHG emissions per capita (p values < 0.001 for all city archetypes). The strongest relationship was for large EU cities (linear increase in emissions with rising *NumP/km*^{2}, $R^2 = 0.72$) and for fast growing urban areas (logarithmic increase, $R^2 = 0.71$). A similar effect was found for urban patches which show a slightly higher degree of soil sealing (i.e., discontinuous low density urban fabric).

Intra-urban distributions and distances to the city center

Results show that, in addition to urban density, the distances of certain LULC classes from the urban center also matter. Areas with a low degree of soil sealing in particular (for example discontinuous (very)

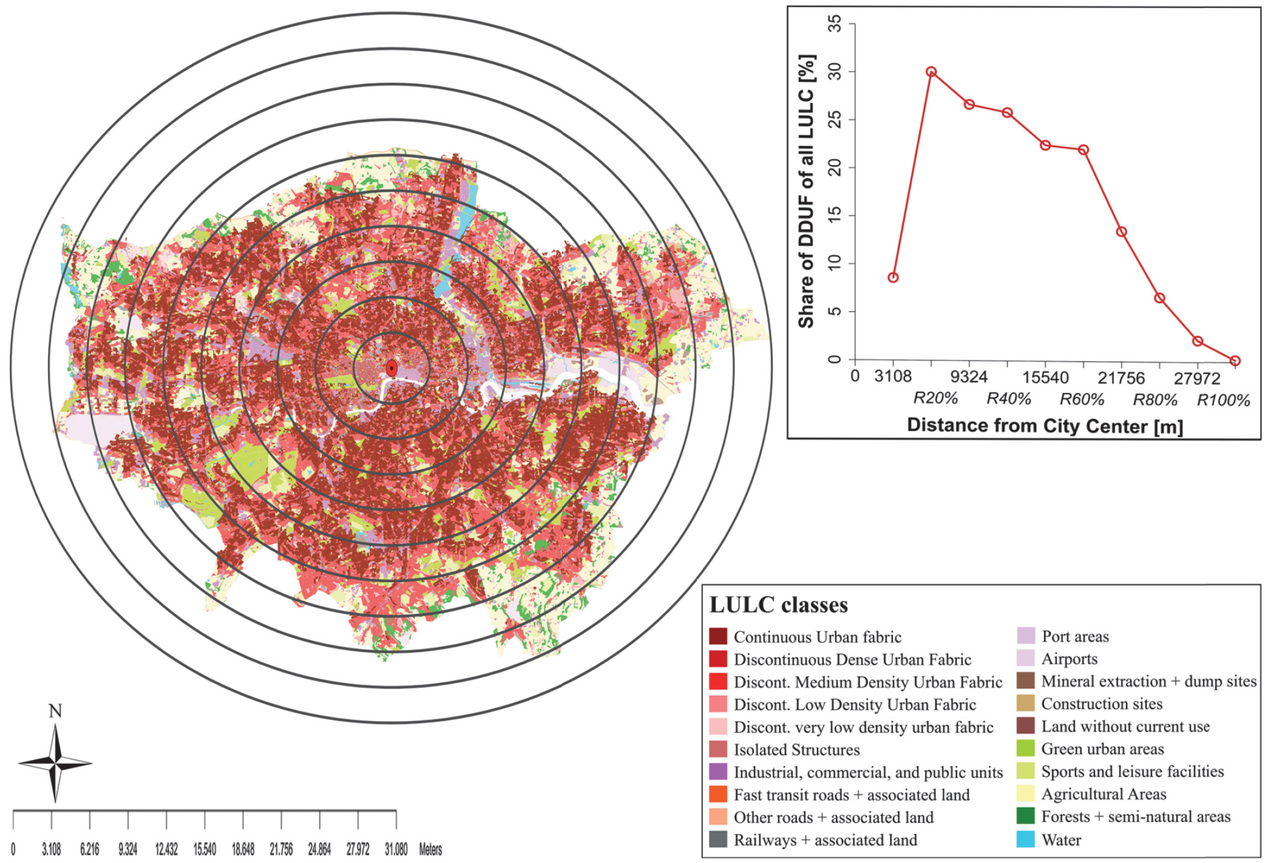

Fig. 1 Calculation of the LULC-based indicators. Using spatial data from European Union's "Urban Atlas", Fig. 1 presents the analysis of the LULC class *discontinuous dense urban fabric* in the city of London. The spatial distribution of the LULC class can be observed from darker patches in the spatial data as well as from the presented graph, which shows its *hotspot* (in 7.5 km distance to the city center) and its *max. distance* (at 32 km from the urban center). *Rings* (R10–R100 %) indicate the relative distances from the city center (10 % steps from city center to the border)

low density urban fabric) were observed to correlate with increasing GHG emissions per capita (p values < 0.001) if located further away from the city center (Table A2; Fig. 4 in Online Appendix 3). The same was found for transport-related LULC classes, which supports previous findings of increased energy consumption with horizontal urban expansion (Norman et al. 2006) and which puts further emphasis on avoiding low-density urban outskirts.

At the same time, more natural sites such as *sports and leisure facilities* and *green urban areas* also correlate with higher GHG emissions per capita (p values < 0.001), when placed further away from the urban center. One explanation could be their importance for residents' well-being. Natural areas provide further ecological services that are especially important for urban inhabitants, for example for recreational and leisure activities (Kumar 2010; Lauf et al. 2014). If such sites are mainly located at the fringe of a city, urban dwellers need to travel longer distances to meet their need for natural areas, which increases their GHG emissions per capita. Previous findings that recreational activities might be particularly related to increasing indirect urban GHG emissions per capita (Jackson and Papathanasopoulou 2008; Druckman and Jackson 2009; Ala-Mantila et al. 2014) support this presented linkage.

LULC composition

The analysis of the urban structure indicators demonstrated that the specific LULC composition can affect a city's GHG emissions. In particular, the spatial density of urban patches was found to be strongly linked to urban GHG emissions per capita. Thus, a high amount of urban patches with a low degree of soil

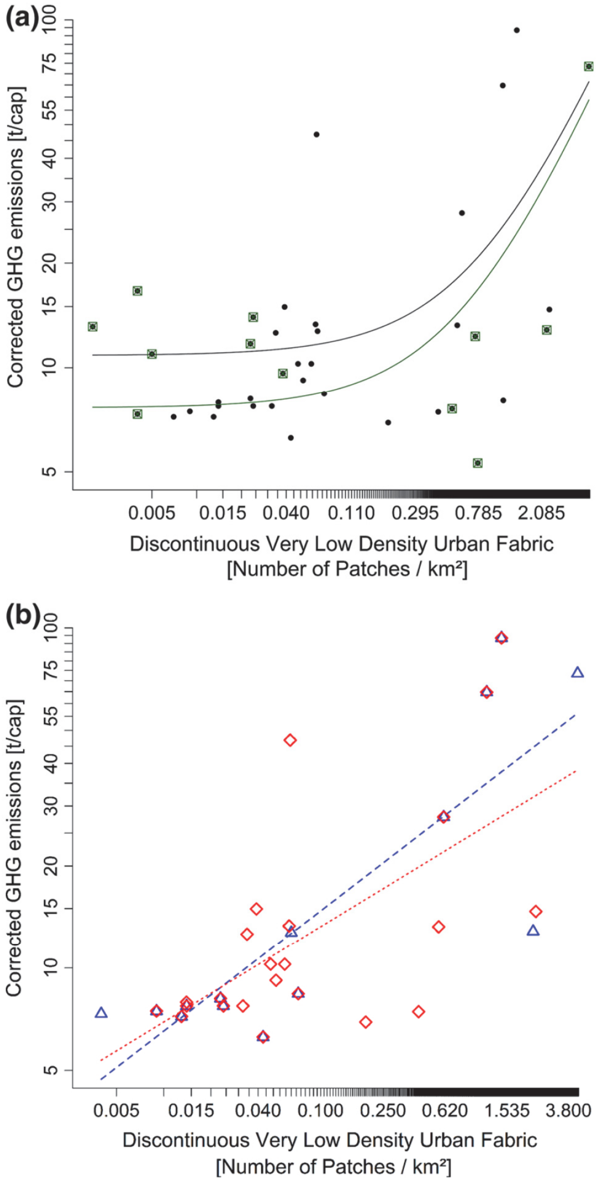

Fig. 2 Urban structure indicator *number of patches/km*^{2} of the LULC class *discontinuous very low density urban fabric*. **a** Linear correlations with urban GHG emissions per capita (*corrected for varying national energy mixes*) are shown for all EU cities (*black dots* and *black solid linear fit-line*, $R^2 = 0.33$) and large cities (*green squares* and *green dot-dashed linear fit-line*, $R^2 = 0.72$), and **b** logarithmic correlations for fast growing urban areas (*blue triangles* and *blue dashed logarithmic fit-line*, $R^2 = 0.71$) and for medium-sized cities (*red diamonds* and *red dotted logarithmic fit-line*, $R^2 = 0.4$). All correlations are statistically significant (p-statistics < 0.001). Please note that due to log–log scaling (*for better readability*) linear trend lines appear bent upwards and logarithmic trend lines are shown as straight lines. (Color figure online)

sealing (e.g., discontinuous (very) low density urban fabric), typical for residential suburbs or urban exurbs, was found to relate to increased GHG emissions per capita in the EU (p values < 0.001, $R^2 = 0.75$–0.87, depending on the city archetype). Also *discontinuous dense urban fabric* (>50–80 % average degree of soil sealing) correlated with GHG emissions per capita (Fig. 3).

As shown in Fig. 3, a higher degree of fragmentation in the *discontinuous dense urban fabric* (higher *edge density*) relates to less GHG emissions per capita. Because such LULC characteristics are typically found in more central urban areas (Herold et al. 2005; European Environment Agency and Meirich 2011), this finding is statically less significant for larger cities, which often grow in more distant urban parts.

In general, a higher patch fragmentation (*edge density*, *mean patch edge*) is found to correlate with reduced GHG emissions per capita. An explanation might be related to a higher connectivity between the urban patches, which further increases the overall density of the urban landscape. Additionally, an increased LULC patch irregularity may also reduce

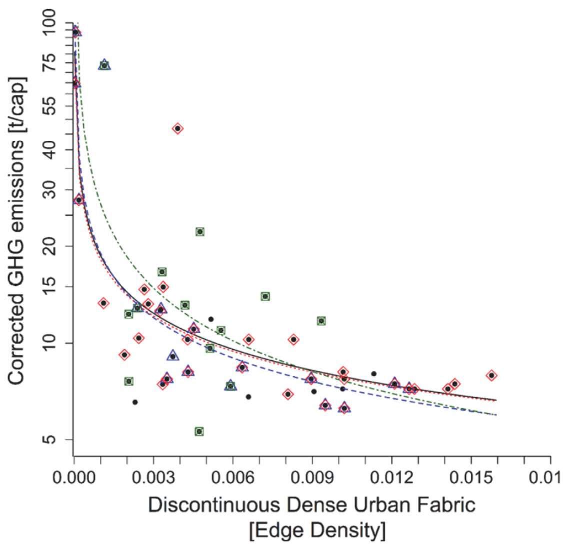

Fig. 3 Correlation between the urban structure indicator *edge density* of the LULC class *discontinuous dense urban fabric* and urban GHG emissions per capita (*corrected for varying national energy mixes*) are shown for all EU cities (*black dots* and *black solid linear fit-line*, $R^2 = 0.57$), medium-sized cities (*red diamonds* and *red dotted logarithmic fit-line*, $R^2 = 0.74$), large cities (*green squares* and *green dot-dashed linear fit-line*, $R^2 = 0.25$), and for fast growing urban areas (*blue triangles* and *blue dashed logarithmic fit-line*, $R^2 = 0.79$). All correlations are statistically significant (p-statistics < 0.001). Please note that the *y-axis* is plotted in log-scale to enhance readability. (Color figure online)

travel distances, and could incentivize more low-carbon transport such as walking or cycling. As the spatial metrics indicator edge density was also recently connected to other important urban processes, such as urban climate control (Weber et al. 2014), its importance (for example in combination with more dense residential areas) should be further investigated for potentials to lower urban GHG emissions per capita.

Supporting the aforementioned findings, larger shares of natural sites (such as forests, parks or water areas) are correlated with higher GHG emissions per capita, especially in large cities (p values < 0.001, $R^2 = 0.7$). As these areas often represent large, clearly defined patches breaking up denser urban fabrics, their linkage to higher GHG emissions can be explained by less compact urban structures and increased intra-urban transport distances. A further reason might be that cities have not adequately taken the GHG reducing effects of natural sites into account when inventorying their GHG emissions. Although this might be expected due to the primary focus of widely-used GHG modelling software on GHG sources (ECOSPEED AG 2012) and not sinks, current research finds that urban nature's GHG sink potential is comparably low and thus, negligible (CAPCOA 2010; Strohbach and Haase 2012; Strohbach et al. 2012).

Conclusions and Outlook

In this study, the use of high spatial resolution LULC data for the analysis of urban GHG emissions is presented in order to re-examine previous findings which mostly investigated socioeconomic urban GHG emissions drivers or selected European cities. Results show that especially urban density, intra-urban distances and specific LULC compositions influence GHG emissions per capita. In summary, this study clearly links a sprawling urban pattern to higher urban GHG emissions per capita. Analyses of the influence of urban shape complexity (Fig. 5 in Online Appendix 4) support this conclusion, demonstrating that a more frayed urban border is related to higher emissions per capita.

Strategies to counteract such developments need to consider urbanites' "[…] desire to realize new lifestyles in the suburban environments, outside the inner city […]" (European Environment Agency 2006), which lead to horizontally expanding cities and increasing land consumption. Therefore, the need in many cities for further outward expansion should be critically questioned. In particular with regard to urban GHG emissions per capita, improving or developing a livable inner-urban area could be more helpful in handling population dynamics and residents' current and future needs for specific urban LULC structures. In this context, the existence of natural sites should be especially considered as they directly affect human well-being, for instance with regard to temperature control, air quality, recreational and leisure activities, and social life (Jenerette et al. 2007; European Environment Agency 2010; Kumar 2010; RWI et al. 2010; Zhao et al. 2011; Strohbach and Haase 2012; Lovell and Taylor 2013; Lauf et al. 2014). As it was found that extensive natural patches might relate to higher GHG emissions per capita, their presence within inner-urban areas should be planned carefully and a smarter way to integrate natural areas and sport and leisure facilities into the urban context needs to be developed. While keeping in mind that the actual composition of urban LULC matters, any solutions should consider a more patchy urban LULC structure due to its demonstrably lower GHG emissions per capita. In this regard, high density urban patches mixed with small-scale greening projects might be examined, as they also "[…] allow for creativity and local empowerment that would inspire broader transformation of green infrastructure at the city level" (Lovell and Taylor 2013).

Investigating a city's LULC composition and spatial structures, which facilitates a uniform representation of the entire urban landscape, proves crucial for analyzing urban GHG emissions. Furthermore, city authorities and urban planners can more easily address the spatial characteristics of a city than change socioeconomic properties or urban lifestyles. This is important for GHG mitigation, but becomes essential for drafting effective urban development master plans (Viegas et al. 2013) that include adequate climate change adaptation measures. However, it should be considered that city-specific topographic situations are expected to be a dominating factor for urban planning. Due to missing data, this parameter could not be directly investigated in this study. Nevertheless, the presented analysis indirectly considers this factor, because all of the presented spatial indicators are also influenced by a city's topography.

Future research should extend the knowledge about spatial drivers of urban GHG emissions to other city archetypes and further regions. In particular, cities in Southern Europe, known for having EU's highest population growth dynamics (European Commission 2007; RWI et al. 2010), should be addressed and cities' specific topographic situations and growth patterns also should be considered. Thus, a change detection analysis of high resolution urban LULC data might deliver interesting findings, which has not yet been possible due to the novelty of the analyzed *Urban Atlas* data. Finally, recognizing both socioeconomic and spatial drivers of urban GHG emissions, a comprehensive methodology needs to be developed that can be easily applied by practitioners to derive possible GHG mitigation options and draft respective urban planning policies.

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Appendices

1.) Basic information about all 52 cities under investigation

Table A1 List of 52 analyzed European cities and their annual total urban GHG emissions (t/capita scope 1 + 2 and upstream emissions for electricity generation) as well as emissions, corrected for varying electricity production methods, incl. the city sizes (km²) and the city size classes according to population sizes: small (**s,** <100,000 inhabitants), medium (**m**, 100,001- 500,000 inhabitants), large (**l**, 500,001- 1mio. inhabitants), million (**mi**, **>** 1mio inhabitants), and population growth rates p.a. over the last 5 years (**decline**,<0.0%; **growth**, 0.01%- 1.0%; **fast growth**, >1.01%), and geographic position (latitudinal and longitudinal coordinates). Socioeconomic data from (Eurostat 2011)

City	Country	**Geographic Position** (lat ; lon)	**City Size** (km²)	**Population Size** (persons in tsd)	**Population Growth** (annual population change of last 5 years)	**CO_2eq emissions** (t/ capita)	**Corrected CO_2eq emissions** (t/ capita)
Aberdeen (m)	UK	-2.05 ; 57.09	186	210.4	0.28	7.7	10.26
Augsburg (m)	Germany	10.54 ; 48.22	146.8	263.313	0.31	9.69	12.61
Belfast (m)	UK	-5.56 ; 54.36	110	268.3	-0.24	7.7	10.26
Birmingham (mi)	UK	-1.54 ; 52.29	268	1019.2	0.57	5.4	7.20
Bologna (m)	Italy	11.2 ; 44.29	140.7	372.256	-0.04	11.1	14.71

Bremen (l)	Germany	8.48 ; 53.5	325.5	547.36	0.09	17.06	22.20
Bristol (m)	UK	-2.35 ; 51.27	117	426.1	1.65	4.7	6.26
Brno (m)	Czech Republic	16.36 ; 49.11	230.2	370.592	0	6.43	7.44
Cambridge (m)	UK	0.7 ; 52.12	41	118.7	1.91	5.8	7.73
Cardiff (m)	UK	-3.11 ; 51.29	139	330.5	1.19	6.3	8.40
Cologne (l)	Germany	6.57 ; 50.56	405.2	995.420	0.6	10.09	13.13
Coventry (m)	UK	-1.31 ; 52.24	98	310.5	0.48	5.2	6.93
Derry (m)	UK	-7.2 ; 55.00	381	109.1	0.48	6.9	9.20
Edinburgh (m)	UK	-3.13 ; 55.57	264	471.7	1.02	6.1	8.13
Essen (l)	Germany	7.1 ; 51.27	210.3	579.759	-0.33	10.75	13.99
Exeter (m)	UK	-3.32 ; 50.43	47.74	118.5	1.21	4.8	6.40
Frankfurt (Main) (l)	Germany	8.41 ; 50.70	248.3	664.838	0.66	12.79	16.64
Freiburg (Breisgau) (m)	Germany	7.51 ; 48.00	153.1	219.665	0.67	7.97	10.37
Glasgow (l)	UK	-4.26 ; 55.86	175	584.2	0.24	8.8	11.73
Hamburg (mi)	Germany	10 ; 53.33	755.3	1772.100	0.43	9.12	11.87
Helsinki (l)	Finland	24.94 ; 60.17	186	549	-	6.01	12.31
Joenkoeping (m)	Sweden	14.1 ; 57.47	1488.8	125.154	1.08	3.19	64.76

Kingston (u.Hull) (m)	UK	-0.2 ; 53.45	71.45	261.100	0.74	5.95	7.93
Leeds (l)	UK	-1.33 ; 53.48	551.72	779.3	1.45	5.5	7.33
Leicester (m)	UK	-1.8 ; 52.38	73.09	303.8	1.37	5.8	7.73
Lincoln (s)	UK	-0.32 ; 53.14	36	88	0.44	5.1	6.80
Liverpool (m)	UK	-2.59 ; 53.25	112	441.1	0.04	5.6	7.46
London (mi)	UK	0.7 ; 51.31	319.3	7668.3	0.77	6.02	8.02
Mainz (m)	Germany	8.16 ; 50.00	97.7	197.623	1.27	8.5	11.06
Manchester (m)	UK	-2.14 ; 53.29	116	473.2	1.82	5.6	7.46
Naples (l)	Italy	14.15 ; 40.5	117.3	973.132	-0.71	4	5.30
Newcastle (u. Tyne) (m)	UK	-1.37 ; 54.58	113	277.8	0.7	6.1	8.13
Nottingham (m)	UK	-1.9 ; 52.57	75	296.6	1.42	5.4	7.20
Nuremberg (l)	Germany	11.5 ; 49.27	186.4	503.638	0.41	7.4	9.63
Oerebro (m)	Sweden	15.13 ; 59.16	1380.1	132.277	1.19	4.6	93.38
Oulu (m)	Finland	25.28 ; 65.3	1411.7	131.585	1.1	13.6	27.85
Porto (m)	Portugal	-8.35 ; 41.1	41.3	216.08	-2.48	7.3	10.26
Portsmouth (m)	UK	-1.5 ; 50.48	40.28	199.4	0.96	5.4	7.20
Prague (mi)	Czech Republic	14.42 ; 50.09	496	1233.211	1.2	7.85	9.08

Sheffield (l)	UK	-1.28 ; 53.23	368	539.8	0.93	5.7	7.60
Stockholm (l)	Sweden	18.06 ; 59.33	188.1	810.12	1.33	3.62	73.48
Stoke on trent (m)	UK	-2.11 ; 53.00	93	239.3	0.01	5.8	7.73
Strasbourg (m)	France	7.45 ; 48.35	78	271.000	-	6.6	46.83
Stuttgart (l)	Germany	9.11 ; 48.47	207.4	600.068	0.37	8.42	10.95
Turin (l)	Italy	7.42 ; 45.4	130.2	908.263	1.06	9.7	12.85
Venice (m)	Italy	12.30 ; 45.26	415.9	268.993	-0.04	10	13.25
Vienna (mi)	Austria	16.37 ; 48.21	414.9	1674.909	1.09	5.19	12.74
Warsaw (mi)	Poland	-2.59 ; 53.20	517.2	1709.781	0.24	6.29	6.54
Wiesbaden (m)	Germany	8.14 ; 50.5	203.9	276.742	0.35	11.5	14.96
Wolverhampton (m)	UK	-2.8 ; 52.35	69	238.1	-0.02	5.4	7.20
Worcester (s)	UK	-2.13 ; 52.12	33	93.9	0.13	5.3	7.06
Wrexham (m)	UK	-2.59 ; 53.2	505	132.7	0.5	10	13.33

2.) All significant relationships between urban GHG emissions and spatial urban properties

Table A2 All significant results (p- value ≤ 0.001; $R^2 \geq 0.4$) from analyses of corrected GHG emission data (if not stated otherwise) of city clusters that were presented in this study. The parameter *max. distance* is always referring to relative distances. LULC classes are sorted alphabetically and follow the nomenclature, used in SIRS (2011)

City cluster	LULC Class	Spatial Parameter	R^2	Trend Type	Trend Intercept	Trend coefficients	Number of cities
All EU cities							**52**
	Discontinuous Dense Urban Fabric	ED	0.58	log	0.1518	-0.373061	52
		NumP/km²	0.43	log	12.855	-0.315857	52
	Discontinuous Very Low Density Urban Fabric	NumP	0.75	linear	9.3834	-0.038357	39
		NumP/km²	0.33	linear	10.8536	12.810205	39
		max. distance	0.41	linear	-1.3146	0.001352	52
	Forests	CA	0.55	linear	10.2864	0	52
	Mineral extraction sites	max. distance	0.42	linear	-2.293	0.001494	50
	Other roads and associated land	hotspot distance	0.4	linear	9.3222	0.001112	48
	Water bodies	CA	0.49	linear	8.511	$1.00\ e^{-06}$	52

		hotspot	0.53	linear	10.087	-0.559072	26
	city level	$PUSH_C$	0.22	log	0.6194	-0.937369	52
Medium-sized cities							**31**
	Agricultural areas, semi-natural areas and wetlands	NumP	0.62	linear	7.1233	0.018283	31
		max. distance	0.53	linear	-3.5136	0.001229	31
	Construction sites	max. distance	0.56	linear	-6.9188	0.001984	31
	Discontinuous Dense Urban Fabric	CA_PER	0.74	log	1.3902	-0.404	31
		ED	0.74	log	0.1629	-0.365259	31
		NumP/km²	0.57	log	11.413	-0.373608	31
	Discontinuous Low Density Urban Fabric	CA	0.66	linear	4.806	$5.00\ e^{-06}$	31
		max. distance	0.62	linear	-6.2087	0.001592	31
	Discontinuous Medium Density Urban Fabric	ED	0.58	log	-0.0425	-0.386762	31
		NumP/km²	0.45	log	11.413	-0.373608	31
		max. distance	0.52	linear	6.5583	0.001615	31
	Discontinuous Very Low Density Urban Fabric	NumP	0.81	linear	9.5715	0.036124	24
		NumP/ km²	0.4	log	1.4036	0.281381	24
		max. distance	0.66	linear	-3.219	0.00161	24

Forests	CA	0.77	linear	9.5093	0	31
	max. distance	0.56	linear	-3.4128	0.001261	31
Green Urban Areas	CA_PER	0.42	log	1.3072	-0.458165	31
	max. distance	0.69	linear	-10.8681	0.002151	31
Industrial, commercial, military and private units	CA_PER	0.6	log	1.7211	-0.67204	31
	ED	0.6	log	-0.6012	-0.652475	31
	max. distance	0.6	linear	-6.9384	0.001578	31
Isolated structures	max. distance	0.55	linear	-2.8818	0.001255	30
Land without current use	CA_PER	0.51	log	0.8623	-0.307287	31
Mineral extraction and dump sites	NumP	0.77	linear	2.6917	1.212256	29
	max. distance	0.68	linear	-4.4965	0.001906	29
Other roads and associated land	hotspot distance	0.6	linear	7.2062	2.0 e^{-04}	29
Railways and associated areas	max. distance	0.68	linear	-9.8287	0.00253	31
Sports and leisure facilities	CA_PER	0.52	log	1.3447	-0.566106	31
	max. distance	0.66	linear	-8.4311	0.001797	31
Water bodies	max. distance	0.57	linear	-2.9401	0.001267	31

		CA	0.79	linear	7.7795	$1.0\ e^{-06}$	31
	city level	CA	0.65	linear	4.766	0	31
	city level	ED	0.47	linear	-0.4477	-1.037194	31
	city level	MPS	0.45	linear	-41.454	0.000424	31
	city level	NumP	0.56	linear	-65.867	$8.0\ e^{-04}$	31
	city level	TE	0.6	linear	-18.759	0	31
Large cities							**13**
	Discontinuous Medium Density Urban Fabric (*with original CO2-data*)	MPE	0.71	log	6.0628	-178.556	13
	Discontinuous Low Density Urban Fabric (*with original CO2-data*)	CA_PER	0.71	log	0.8563	-0.19041	13
		NumP/km²	0.67	log	0.8173	-0.232105	13
	Discontinuous Very Low Density Urban Fabric	NumP	0.79	linear	7.3338	0.068853	12
		NumP/km²	0.72	linear	7.6418	11.810266	12
	Green Urban Areas	CA_PER	0.7	linear	-8.7417	3.680569	13
	Water bodies	hotspot	0.99	linear	10.387	0.647569	6
		dev. of trend	0.94	linear	11.9332	13298.3939	13

Fast growing cities							**17**
Discontinuous Dense Urban Fabric	ED	0.79	log	0.0267	-0.417205	17
	NumP/km²	0.73	log	1.3277	-0.401401	17
Discontinuous Low Density Urban Fabric	NumP	0.79	linear	4.1018	0.06727	16
Discontinuous Very Low Density Urban Fabric	NumP	0.87	linear	8.1214	0.040733	14
	NumP/km²	0.71	log	1.5235	0.354647	14
Forests	NumP	0.62	linear	9.9552	0.31353	17
Land without current use	ED	0.67	log	-0.7588	-0.470297	17
	NumP/km²	0.61	log	0.8188	-0.402114	17
Sports and leisure facilities	CA_PER	0.63	log	1.5316	-0.771522	17
Industrial, commercial, military and private units	ED	0.57	log	-0.7987	-0.752148	17
Isolated structures	CA	0.61	linear	11.6876	$5.0\ e^{-06}$	16
Other roads and associated land	hotspot	0.77	linear	75.2284	-0.721483	14
Railways and associated areas	ED	0.54	log	-2.3409	-1.034453	17
Water bodies	max. distance	0.54	linear	-3.9054	0.001468	17
city level	CA	0.56	linear	57.031	0	17
city level	$PUSH_C$	0.6	log	0.006	-2.384898	17

3.) Correlations between maximum ranges of selected LULC classes from the city center and urban GHG emissions per capita (for medium-sized cities)

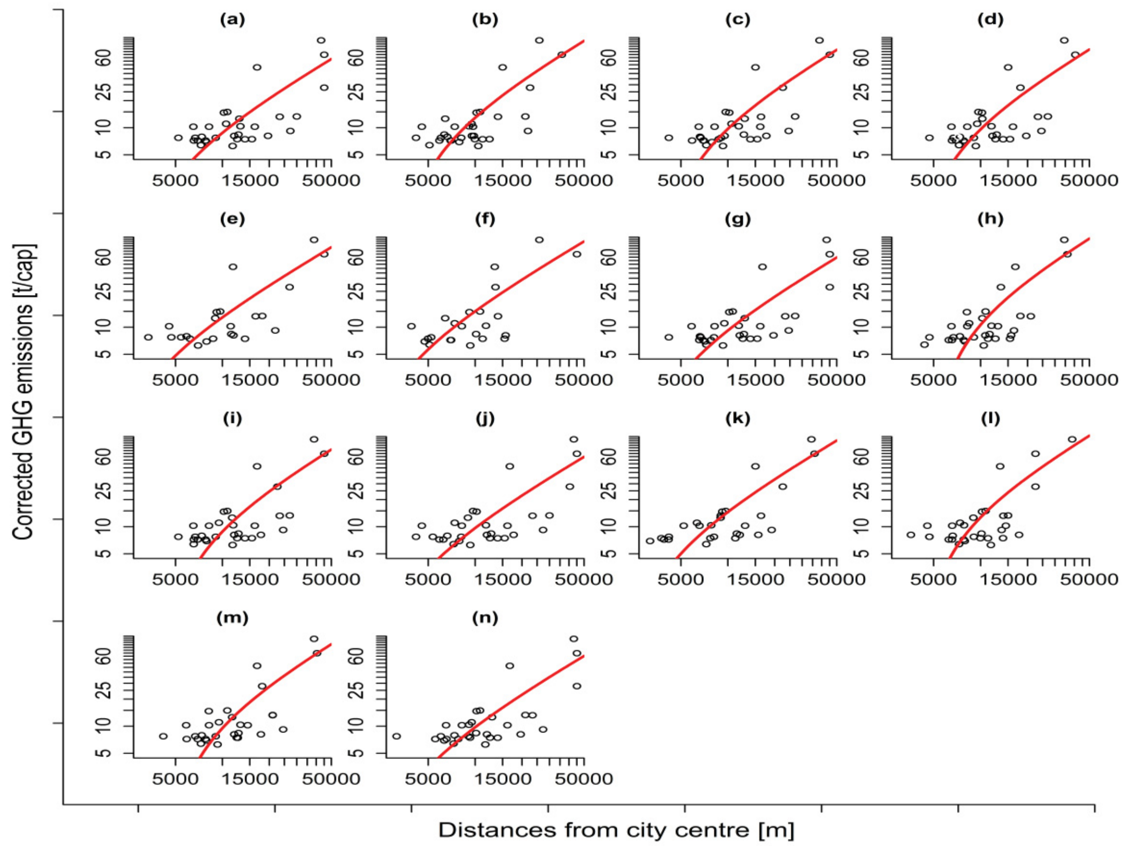

Fig. 4 LULC classes in medium-sized cities, highlighting the importance of the LULC-based indicator *max. distance* for assessing urban GHG emissions. Linear correlations between GHG emissions per capita (*corrected for varying national energy mixes*) and max. distances are presented for the LULC classes **(a)** *Agricultural + Semi-natural areas + Wetlands*, **(b)** *Construction sites*, **(c)** *Discontinuous Low Density Urban Fabric*, **(d)** *Discontinuous Medium Density Urban Fabric*, **(e)** *Discontinuous Very Low Density Urban Fabric*, **(f)** *Fast transit roads and associated land*, **(g)** *Forests*, **(h)** *Green urban areas*, **(i)** *Industrial, commercial, military and private units*, **(j)** *Isolated Structures*, **(k)** *Mineral extraction and dump sites*, **(l)** *Railways and associated land*, **(m)** *Sports and leisure facilities*, **(n)** *Water bodies* in log-log plots to enhance readability. All correlations are statistically significant (p-statistics < 0.001; R^2 >0.5; specific results can be found in Table A2). Please note that due to the log-log scaling, linear fit lines are not presented as straight lines.

4.) Linkage between the complexity of the overall urban shape and the urban GHG emissions per capita

To analyze the complexity of the urban shape, each urban area was spatially defined by extracting administrative city boundaries from the UA data. Using the ArcGIS tool “Bounding containers” (Petterson 2010) the smallest possible circle was then calculated around each city. Assuming that a larger difference between the actual area of a city and the area of the calculated circle corresponds to a more complex, potentially more frayed pattern of city growth, the following urban shape complexity parameter (**$PUSH_C$**) was derived for all cities under investigation:

$$PUSH_C = \frac{Urban\ area\ [km^2]}{Area\ of\ constructed\ minimal\ cirlce\ [km^2]} \quad \textbf{(1)}$$

***P**arameter of **U**rban **Sh**ape **C**omplexity (**$PUSH_C$**) calculated using a constructed circle; with $PUSH_C$ between 0 (very complex urban growth) and 1 (perfect circular urban growth)*

In order to differentiate the $PUSH_C$ index from other complexity indices, it was compared to the commonly used “Edge density”. It was found that both indices are weakly correlated (correlation coefficient: -0.042). Additionally, a linear regression analysis revealed no relationship (R^2: 0.002; p-value: 0.77). Although not all relations to known complexity measures were analyzed, it can be assumed that the introduced factor contains at least partially new information on the complexity of the shape of a city.

Results present a relationship between the form of urban expansion and per capita GHG emissions, which is also supported by findings from Ou et al. (2013). This relationship could be detected for all EU cities under investigation with the highest significance for fast growing cities. A possible explanation is that, due to urbanites’ “[…] desire to realize new lifestyles in the suburban environments, outside the inner city […]” (European Environment Agency 2006), growing EU cities are horizontally expanding and increasingly consuming land. If such an urban expansion is accompanied by a more complex city growth (e.g., a more frayed expansion), longer distances to the city center have to be travelled or commuted, thus increasing the total urban GHG emissions per capita.

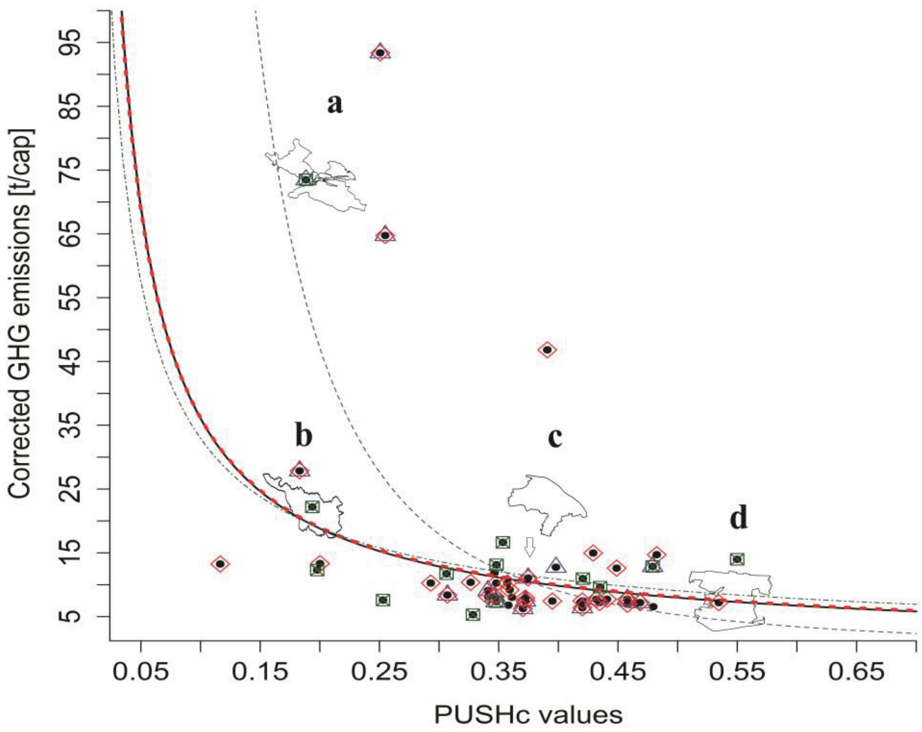

Fig. 5 *$PUSH_C$* indicator presenting correlations between a city's shape complexity and the GHG emissions of its inhabitants (*corrected for varying national energy mixes*). Correlations are shown for *all EU cities* (black dots and black solid linear fit-line, R^2 =0.22, p-statistics =<0.001), *medium-sized cities* (red diamonds and red dotted logarithmic fit-line, R^2 =0.20, p-statistics =0.01), *large cities* (green squares and green dot-dashed linear fit-line, R^2 =0.19, p-statistics =0.13), and for *fast growing urban areas* (blue triangles and blue dashed logarithmic fit-line, R^2 =0.6, p-statistics =<0.001). Additionally, the respective urban shapes of the cities Bremen (**b**), Mainz (**c**), Portsmouth (**d**), and Stockholm (**a**) are shown, illustrating the relevance of the $PUSH_C$ indicator for controlling urban GHG emissions.

Part IV

Research publication 3

Estimating greenhouse gas emissions of European Cities

- Modeling emissions with only one spatial and one socioeconomic variable

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Abstract

Motivation

Cities, being important GHG emitters, play a key role in fighting climate change. Socioeconomic and spatial urban GHG influences have already been identified, and there are promising linkages between cities' emission reduction strategies and urban development and policy-making. However, simpler approaches are needed to help cities identify their most important emission drivers.

Objectives and methodology

In analyzing 44 European cities, this study identifies the most significant socioeconomic and spatial GHG determinants. Multiple statistical analyses are then used to develop a straightforward approach for estimating urban emissions.

Results and conclusions

In particular, the average household size and the edge density of discontinuous dense urban fabric correlate with urban GHG emissions. A statistical model can be developed with both variables explaining 86% of the total variance of GHG emissions of EU cities (controlling for varying electricity CO_2 intensities). In a test for 10 additional EU cities, the approach proves suitable for helping cities estimate their GHG emissions and thus, develop adequate climate change mitigation strategies.

Zusammenfassung

Motivation

Städte, verantwortlich für den Großteil der globalen THG Emissionen, sind wichtige Akteure im Kampf gegen den Klimawandel. Sozioökonomische und räumliche urbane Emissionseinflüsse wurden bereits identifiziert und die Verknüpfung von Stadtplanung und -politik mit Emissionsreduktionsstrategien erscheint vielversprechend. Es benötigt jedoch einfacherer Methoden für Städte, ihre Hauptemissionstreiber zu identifizieren.

Ziele und Methodik

Es werden verschiedene sozioökonomische und räumliche Parameter auf ihren Emissionseinfluss in 44 Europäischen Städten untersucht. Im Anschluss helfen multiple, statistische Analysen, einen einfacheren Ansatz zur Emissionsabschätzung zu entwickeln.

Resultate und Schlussfolgerungen

Speziell die Haushaltsgröße und die „Kantendichte der diskontinuierlich dichten Stadtareale“ (*edge density of discontinuous dense urban fabrics*) korrelieren mit urbanen THG Emissionen. Ein gemeinsames statistisches Modell erklärt 86% der analysierten Emissionen und ein Test für 10 weitere EU Städte zeigt, dass das Modell hilfreich ist, urbane Emissionen abzuschätzen und Reduktionsmaßnahmen zu identifizieren.

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Estimating greenhouse gas emissions of European cities — Modeling emissions with only one spatial and one socioeconomic variable

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HIGHLIGHTS

- Two variables determine urban GHG emissions in Europe, assuming equal power generation.
- Household size, inner-urban compactness and power generation drive urban GHG emissions.
- Climate policies should consider these three variables.

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ABSTRACT

Substantive and concerted action is needed to mitigate climate change. However, international negotiations struggle to adopt ambitious legislation and to anticipate more climate-friendly developments. Thus, stronger actions are needed from other players. Cities, being greenhouse gas emission centers, play a key role in promoting the climate change mitigation movement by becoming hubs for smart and low-carbon lifestyles. In this context, a stronger linkage between greenhouse gas emissions and urban development and policy-making seems promising. Therefore, simple approaches are needed to objectively identify crucial emission drivers for deriving appropriate emission reduction strategies. In analyzing 44 European cities, the authors investigate possible socioeconomic and spatial determinants of urban greenhouse gas emissions. Multiple statistical analyses reveal that the average household size and the edge density of discontinuous dense urban fabric explain up to 86% of the total variance of greenhouse gas emissions of EU cities (when controlled for varying electricity carbon intensities). Finally, based on these findings, a multiple regression model is presented to determine greenhouse gas emissions. It is independently evaluated with ten further EU cities. The reliance on only two indicators shows that the model can be easily applied in addressing important greenhouse gas emission sources of European urbanites, when varying power generations are considered. This knowledge can help cities develop adequate climate change mitigation strategies and promote respective policies on the EU or the regional level. The results can further be used to derive first estimates of urban greenhouse gas emissions, if no other analyses are available.

1. Introduction

Climate change is upon us (EEA, 2014), and cities play a key role in managing its anthropogenic drivers and environmental effects (Heidrich et al., 2013; Reckien et al., 2014). They are home to more than 53% of the global population with numbers rising (The World Bank Group, 2014) and will inevitably have to cope with the impacts of changing climatic patterns due the additive microclimatic characteristics of cities (Hallegatte, 2009; IPCC, 2014a; McDonald et al., 2014; Patz et al., 2014). Concurrently, concentrating on the main drivers of greenhouse gas (GHG) emissions they are expected to be responsible for up to 70% of global emissions (United Nations Human Settlement Programme, 2011) and thus directly affecting the intensity of future climatic changes (IPCC, 2014b). Minding their importance to the global climate, cities are urged to promote sustainable development and lifestyles leading to lower GHG emissions per inhabitant (Glaeser and Kahn, 2010; Hoornweg et al., 2011; Ala-Mantila et al., 2014).

Therefore, more knowledge is needed to understand the interactions between cities and the climate system (Romero Lankao and Dodman, 2011) to generate standardized approaches to assess urban GHG emissions. Although international standards for GHG inventorying are currently being developed (Bhatia and Ranganathan, 2004; UNFCCC, 2007; C40 Cities, 2012), a more applicable and easily reproducible approach that integrates the biggest emission drivers is still lacking, especially for cities.

In the presented study, it is therefore hypothesized that considering only few socioeconomic and spatial indicators is sufficient to estimate a

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city's GHG emissions. By analyzing previously found potential GHG determinants, the presented study identifies the most significant emission drivers and thus, essentially contributes to the closing of this research gap. In this regard, it was shown that the specific energy mix can strongly influence urban GHG emissions (Kennedy et al., 2009a; Baur et al., 2013). Moreover, certain socioeconomic and demographic variables, as well as spatial patterns and land use and land cover (LULC) characteristics of cities were found to correlate with GHG emissions (Baur et al., in press; Kennedy et al., 2009b; Marcotullio et al., 2013).

Focusing on the most significant emission drivers of 44 European cities, multiple statistical analyses are conducted to develop an easy-to-apply model that supports estimating urban GHG emissions and finding possible emission mitigation strategies. In particular, the consideration of spatial data is expected to help in comparatively assessing emissions. By investigating ten further EU urban areas the quality of the presented model is validated in order to prove its usefulness for estimating urban GHG emissions. In the end, the results can be used to derive possible climate change mitigation strategies or compare respective best practice examples. The findings will also help to draft appropriate urban planning policies to adapt Europe's cities to changing climatic conditions.

2. Material and methods

2.1. Data

For analyzing the most influential GHG emission drivers of European cities, both socioeconomic as well as spatial properties were investigated. The cities under investigation present different city archetypes, according to specific socioeconomic structures, spatial patterns, or regional distributions.

Information about the GHG emissions per capita is based on the emission data set developed by Baur et al. (2013). In the original data set, urban scope 1 and 2 CO_2eq emissions (Bhatia and Ranganathan, 2004) are included for 62 European cities. Additionally, emission data consider upstream emissions for energy production and corrections for seasonal variations. When breaking down national GHG emissions by sectors (averages for 1990–2004), 29.39% of the urban GHG emissions can be attributed to cities' electricity production (The Shift Project, 2012). However, depending on the national energy mix, the electricity CO_2 intensities vary strongly between European countries. Thus, the influence of electricity production (subsequently: electricity GHG emissions) on total urban GHG emissions also varies between cities. To balance out this varying importance of electricity in urban GHG inventories, a uniform CO_2 intensity was assumed for 30% of the reported specific urban CO_2eq emissions. The resulting corrected GHG data (CO_2eq-c) can then be analyzed for further GHG drivers other than electricity production (Table A.2 in the appendix lists all analyzed socioeconomic variables).

Considering earlier findings (Newman and Kenworthy, 1989; Kennedy et al., 2009b; Baur et al., 2013), possible socioeconomic GHG drivers are the average household size (in terms of number of people per household) and the population density of the cities under investigation. Therefore, population density data were calculated from specific city sizes and from census data, both taken from the Eurostat's databases (Eurostat, 2011). Data were assessed between 2007 and 2009. The same data source was used to obtain information about the city-specific average household sizes (assessed between 2003 and 2006). For analyzing the important spatial drivers of urban GHG emissions, a number of widely-applied landscape metrics and LULC-based indicators of various LULC classes were considered (Baur et al., in press; Herold et al., 2005; Zhou et al., 2011; Lauf et al., 2014). The original LULC data came from the Urban Atlas (UA) project (European Commission, 2011). The original UA data covers both built-up areas as well as non-built-up areas, and includes 305 major European agglomerations. It contains information on 20 different LULC classes at a geographical scale of 1:10,000, and the image reference year was 2006 (±1 year). Table A.2 in the appendix lists all analyzed spatial variables; for further information about the UA data or the covered LULC classes, please refer to the project's final report published by SIRS (2011). Considering all data sources, data sets for 44 of the above-introduced European cities were utilized for modeling urban GHG emissions.

For validation purposes, ten additional urban areas were investigated that were not included in the original model. In this regard, the main selection criteria included the availability of a comparable data basis for the cities (GHG, socioeconomic, spatial) and a representative variation of city sizes and spatial distribution across Europe. Thus, the GHG emissions of the cities of Dresden and Regensburg (Germany), Madrid and Málaga (Spain), Cardiff and Manchester (UK), Nantes and Paris (France), and Brno and Prague (Czech Republic) were selected.

In Table A.1 detailed information about all analyzed cities and the considered data is provided.

2.2. Identification of significant GHG emission drivers

The variables from Tables A.2 were utilized to develop a multiple regression model to explain the GHG emission drivers of the 44 EU cities, listed in Table A.1. Analyses on the introduced CO_2eq-c emissions were conducted with the software package "R" (R Development Core Team, 2012). To ensure the statistical independence of possible emission drivers, potential determinants were checked for multicollinearity and autocorrelation. Therefore, the Variance Inflation Factor (upper limit: 10) and the Durbin Watson test (lower limit: 1.5; upper limit: 2.5) were applied (Backhaus et al., 2010; Black and Babin, 2009; Reinboth, 2007).

To identify a suitable multiple-regression model (good statistical quality with reduced model complexity) for investigating urban GHG emissions, "Akaike's information criterion — AIC" (Crawley, 2013) was used. If the identified model still includes insignificant variables (F-statistics), specific p-values of variables were considered for focusing on the most significant influences on urban GHG emissions (Backhaus et al., 2010).

2.3. Independent validation of the GHG regression model

To validate the quality of the developed GHG regression model, the resulting values were compared to the original and independent GHG data reported by city administrators. Because modeled values reflect emissions that are corrected for varying energy CO_2 intensities (CO_2eq-c.), a correction factor (δ) was introduced, which presents the ratio between CO_2eq and CO_2eq-c. This factor is used in Eq. (1) and allows a comparison between the modeled (CO_2eq-m) and the reported GHG emissions (CO_2eq). City-specific information about all parameters and GHG emission data can be found in Table A.1.

3. Results and discussion

3.1. Identification of significant GHG emission drivers

Statistical analyses (Section 2.2) resulted in the following final multiple linear model (Eq. (1)). The corresponding statistics are shown in Table 1.

$$CO_2eq{-}m = 10^{0.89-1.87*\mathrm{Lg}\,(HH)-0.32*\mathrm{Lg}\,(ED\ \ DDUF)} * \delta \qquad (1)$$

Table 1
Statistics of the final regression model, showing a strong influence of household size (HH) and edge density of the LULC class discontinuous dense urban fabric (ED DDUF) on the corrected GHG emissions of European urbanites (CO_2eq-c).

Variables	Coefficients	Std. error	p-Values (F-statistics)
Intercept	0.89267	0.13417	5.10e-08***
Lg (HH)	−1.87292	0.31583	5.44e-07***
Lg (ED DDUF)	−0.31632	0.02465	6.03e-16***

Significance: '***' = p-value < 0.001.
Adjusted R-squared: 0.86, p-value: <2.2e-16, F-statistic: 131.2 on 2 and 41 DF.

In Eq. (1), GHG emissions (CO_2eq-m) are estimated by a linear model of the independent variables household size (*HH*) and edge density of the LULC class discontinuous dense urban fabric (*ED DDUF*). Both variables logarithmically correlate with GHG emissions per capita. Household size describes the average number of persons in one household and the edge density represents a perimeter/area-ratio for the discontinuous dense urban fabric. This spatial measure thus informs about the degree of complexity of the analyzed discontinuous dense urban patches. This LULC class is typical for inner-city residential areas and mainly describes urban patches that show a high degree of soil sealing (50%–80%). The combination of edge density and discontinuous dense urban fabric will be referred to as dense inner-urban areas in the following sections.

Further information about the analyzed LULC classes as well as the spatial indicators can be found in Table A.2.

It is shown that the household size and edge density of the LULC class discontinuous dense urban fabric have a significant influence on urban GHG emissions per capita. Both variables negatively correlate with CO_2eq emissions. The final regression model successfully reflects both influences and can be used to explain 86% of the total variation in the GHG data.

The significant connection ($p < 0.001$) between urban GHG emissions and both influences is shown in Fig. 1. Here, bubbles depict the GHG emissions per capita of all EU cities under investigation. They are scaled according to the specific GHG emissions and spaced with respect to the individual average household sizes and edge densities of the discontinuous dense urban fabric. Additionally, the emissions of an average EU city are calculated.

It can be observed that a combination of large average household sizes and very compact inner-urban areas (high edge density of discontinuous dense urban patches) results in less GHG emissions per capita. Contrastingly, smaller household sizes and less dense inner-urban areas seem to correspond to higher GHG emissions per capita.

A blue dashed bubble symbolizes the GHG emissions per capita (7.25t) of an average EU city with a mean household size (2.15) and an average edge density of the discontinuous dense urban fabrics (0.006) in the data set.

The investigated UK cities in particular are characterized by above-average household sizes and complex discontinuous dense urban fabrics. The amount of household members corresponds to national averages of 2.3 (Office for National Statistics, 2013) and is due to a lower amount of single person households and an above average number of extended families (Iacovou and Skew, 2011), compared to other North-Western EU nations. The high edge densities of the discontinuous dense urban fabrics are related to specific historic urban developments. Many urban advancements, for example, were influenced by the industrial revolution (HistoryLearningSite.co.uk, 2008). Also, the Green belt-concept, which aimed at preventing urban sprawl (Campaign to Protect Rural England et al., 2010; Quilty-Harper, 2012; Smith, 2014) led to more compact inner-urban areas.

Furthermore, the noted effect of national electricity GHG emissions can be observed. As an example, the city of Oerebro (#32) is shown to emit comparably few emissions per capita, despite a small household size and low edge density of the discontinuous dense urban fabric. The reason can be found in very low electricity intensities, which, independent from the model variables, lead to lower GHG emissions per capita. This applies to the Swedish cities whose electricity mix contained only 15g CO_2/kWh in 2008 (Oesterreichs Energie and Eurelectric, 2012), as well as e.g., to Helsinki (#19, Finland, 219g CO_2/kWh), Joenkoeping (#20, Sweden, 15g CO_2/kWh), and to a lesser extend to Vienna (#40, Austria, 168g CO_2/kWh), which generates most of its electricity from hydro power. In comparison, the EU27 average is 390g CO_2/kWh in 2008, with the most CO_2 intense electricity generation in Greece with 950 g CO_2/kWh in 2008 (Oesterreichs Energie and Eurelectric, 2012). Further information about the analyzed GHG emissions can be found in Table A.1 and the respective CO_2-intensities of the national electricity productions were published by Oesterreichs Energie and Eurelectric (2012).

3.2. Validation of the GHG model

At first the model output was validated by comparing modeled GHG emissions with reported GHG emissions (Fig. 2). In a second step, the

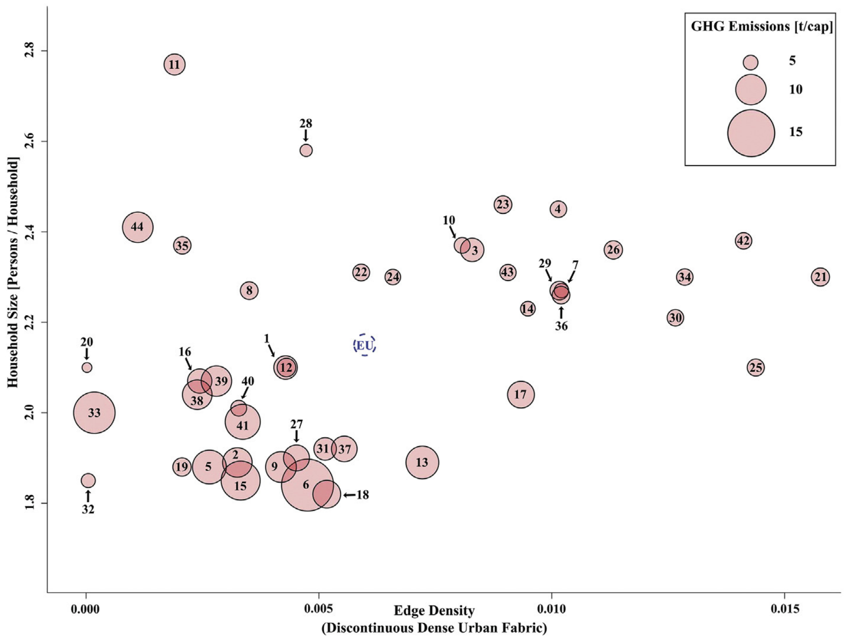

Fig. 1. Scatter plot, showing a significant influence ($p < 0.001$) of the household size and the edge density of discontinuous dense urban fabric on the reported CO_2eq emissions of 44 European cities (shown as bubbles). Bubble sizes represent emissions per capita (values are squared to ease differentiation). The blue dashed bubble indicates the EU mean values. Numbers indicate specific cities; corresponding city names and specific GHG information are shown in Table A.1.

model was used to calculate GHG emissions of ten independently considered cities to test the model quality (Section 2.3).

As already shown by the statistical results (Table 1), the model (blue diamonds) is suitable for estimating the original GHG emissions (red dots in Fig. 2). The relative deviation between modeled and reported GHG emissions per capita is only 5.8% for the average EU city. A more precise look at Fig. 2 shows that 73% of the modeled GHG emissions per capita have a variation of less than 20% from the reported values, and 39% vary less than 10%. In general, 45% of the modeled results underestimate original GHG emissions and 55% of the modeled results present higher values than the reported ones.

The main reasons for these deviations are related either to strongly diverging electricity GHG emissions, or to extraordinary values of both model variables. Some explanations concerning the revealed underestimation or overestimations of the reported GHG emissions are provided below.

In the case of Bremen (#6), the original emissions are higher than their modeled counterparts. This is due to reported GHG emission values that are almost twice as high as Germany's average GHG emissions per capita. The main reason is inefficient and coal-dominated electricity generation, leading to above-average electricity CO_2 intensity. The model, however, only integrates national average electricity GHG emissions, which presents a possible overall model uncertainty as described in Section 3.3. Additionally, Bremen's industry is largely related to energy-intensive steel production (BUND, 2008). Both factors finally result in high GHG emissions per capita that can only partly be explained by the model's variables, which focus less on electricity generation or industrial processes.

For the city of Oerebro (#32), the model is also not fully able to sufficiently estimate the reported GHG emissions. Again the related method of energy mix correction (Section 2.3) gives an indication: at the time when the reported GHG emissions were calculated, almost 90% of the Swedish electricity was produced from nuclear and hydropower (World Nuclear Association, 2014). Thus, the Swedish electricity mix contained very low CO_2 and required, according to Eq. (1), a very strong correction of the modeled GHG emissions per capita (CO_2eq-m). This strong δ overcorrected the modeled emissions and thus led to a 38% variation that can hardly be explained by the model variables.

In contrast, the model overestimates the GHG emissions of urban dwellers for Helsinki (#19) and Sheffield (#35). With regard to Helsinki, higher GHG emissions are estimated because of very small household sizes and a very low edge density of a small amount of discontinuous dense urban patches. Furthermore, more than 70% of Helsinki's GHG emissions are caused by electricity consumption (Anderson et al., 2011), which is a much larger share than assumed for the applied correction (Section 2.1) and correspondingly results in slightly undercorrected modeled GHG emissions.

For Sheffield the model resulted in the strongest overestimations of urban GHG emissions, even though Sheffield's residents live in slightly above-average sized households. However, in comparison to other UK urban areas, the city's spatial layout is characterized by the smallest edge density of the discontinuous dense urban fabric. An explanation can be found in Sheffield's historic industrial role as one of UK's most important steel manufacturing sites (Simpson, 2009), which was characterized by controlled urban development with uniformly dense (mainly residential) inner-urban structures. Recent initiatives (e.g., the "Green and Open Space strategy") promote this trend by counteracting excessive compaction of urban structures (Styles, 2011).

The results of the independent model validation show a similar variation of GHG emissions compared to those for the initial 44 cities used in the model construction (Figs. 2 and 3). This confirms the ability to transfer the model to further European cities. 50% of the modeled cities' GHG emissions vary less than 20%, and 20% vary less than 10%. In general, 50% of the modeled results are underestimated with the strongest variations found for the French cities Nantes (−70%) and Paris (−34%); the highest overestimations occurred for Málaga (30%). As already explained for the Swedish cities (Figs. 1 and 2), the observed underestimation for Nantes and Paris might be due to a very low CO_2 intensity in the French electricity mix, with 90% nuclear and renewable energy sources (46 g CO_2/kWh in 2008). As a consequence, the model's correction factor δ overcorrects the modeled results, leading to very low GHG emission estimates. For Nantes, a further distorting effect comes from its specific electricity production, which is more CO_2-intense than the French average (Quero, 2010). A very Paris-specific peculiarity is its predominant amount of continuous dense urban fabrics within the considered city borders. In contrast, the discontinuous dense urban

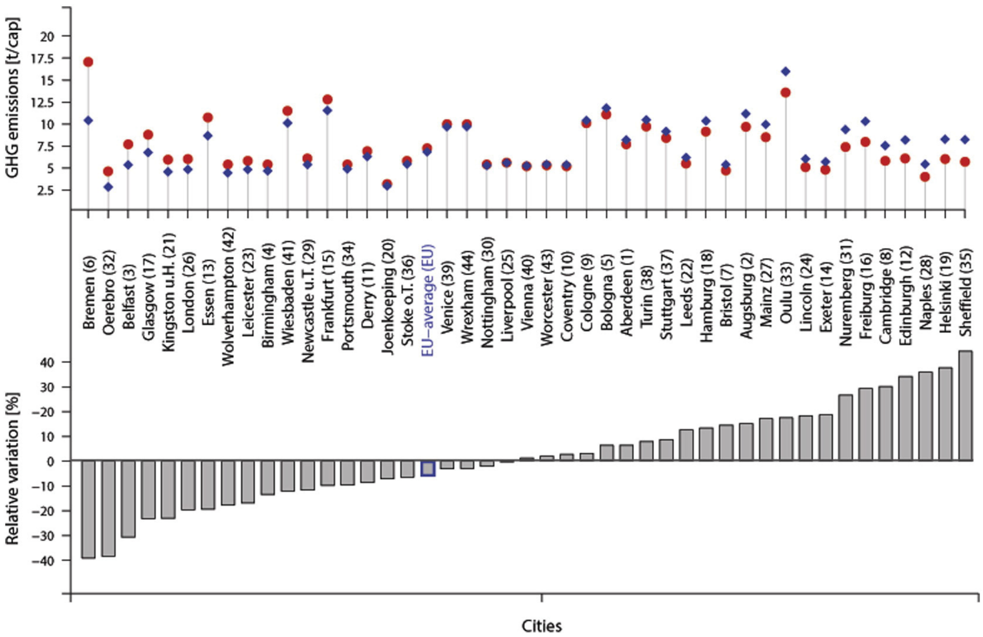

Fig. 2. Top: Modeled GHG emissions per capita (CO_2eq-m, blue diamonds) compared to the reported GHG data (CO_2eq, red dots) for 44 EU cities (sorted according to degree of variation; specific values are shown in Table A.1); Bottom: Bar chart indicating city specific variations between modeled and the reported GHG emissions (sorted according to degree of variation).

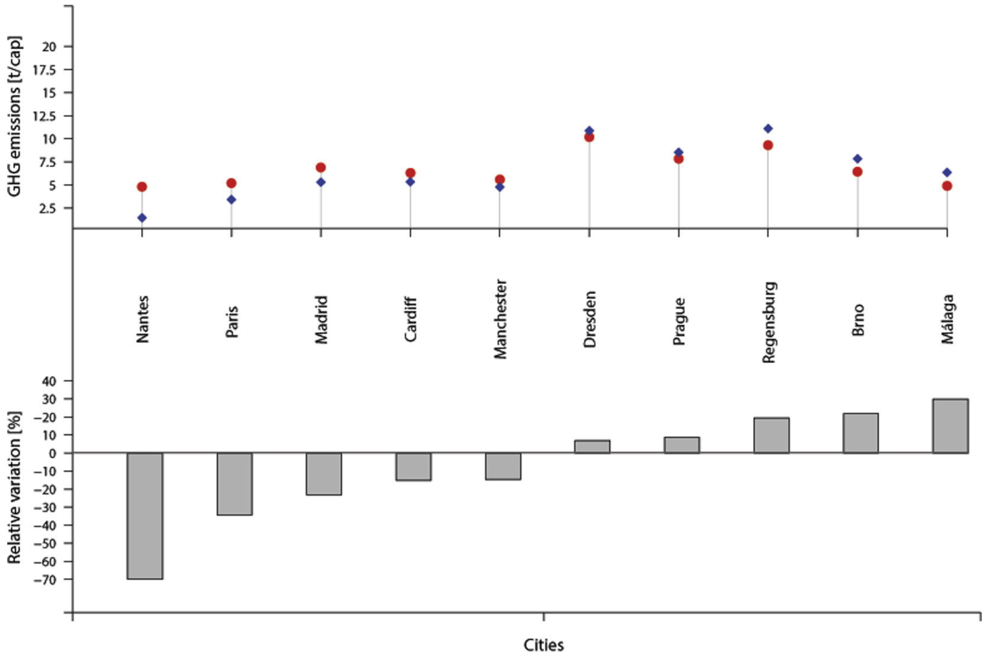

Fig. 3. Top: Modeled GHG emissions per capita (CO_2eq-m, blue diamonds) compared to the reported GHG data (CO_2eq, red dots) for ten further, independently selected EU cities (sorted according to degree of variation; specific values are shown in Table A.1); Bottom: Bar chart indicating city specific variations between modeled and the reported GHG emissions (sorted according to degree of variation).

fabric is underrepresented and respective patches have a comparably low edge density. This results in a false assumption of the GHG emissions in the model.

The observed 30% overestimation for Málaga is mainly based on the city's very low edge density of the discontinuous dense urban fabric (0.0007), which is six times smaller than the average values. This consequently results in comparably high modeled GHG emissions per capita.

3.3. General discussion

The presented results have proven that the introduced multiple regression model is able to estimate urban GHG emissions in Europe by only considering two variables for the generally complex calculation of GHG emissions (if emissions from the electricity generation are considered). These two variables are the average household size of a city's residents and the edge density of the specific urban LULC class discontinuous dense urban fabric. For the model setup and validation, different European cities in terms of size, form and spatial distribution across Europe were analyzed (Table A.1 in the Appendix A). This confirms its wide applicability for different European city types independent of specific national or regional characteristics.

The demographic indicator household size is revealed to significantly affect the urban system. This is shown, for example, in terms of specific LULC and urban patterns due to the respective household demands in residential living space (Buzar et al., 2005; Lauf et al., 2012; Haase et al., 2013), or with regard to household-related energy consumption patterns (Wei et al., 2014). Considering demographic change and the accompanied trend of decreasing family households, as well as increasing numbers of smaller households, this illustrates the relevance of household sizes as a crucial indicator for future urban development and energy consumption (Alders and Manting, 2001; Sinclair, 2004; Surkyn and Lesthaeghe, 2004).

The respective decrease of per capita GHG emissions with increasing household size can be explained by economies of scale (Büchs and Schnepf, 2013). Thus, not only home energy use, but also transport needs, food and other every day goods can be used more efficiently. This lowers the total emissions of each resident (Baur et al., in press; Ala-Mantila et al., 2014), although the precise influences are still under discussion. For Finnish cities, Ala-Mantila et al. (2014) assume that the described economies of scale mainly affect direct GHG emissions (primarily related to energy, transport, and buildings), rather than indirect emissions (specifically those related to the service sector). They even found that in metropolitan areas, indirect service-related emissions in particular are slightly increasing with growing household sizes. This finding is in line with earlier results that relate large shares of private household GHG emissions especially to leisure and recreational activities, which are both related to an increasing demand for services (Jackson and Papathanasopoulou, 2008; Druckman and Jackson, 2009).

Considering the influence of the edge density of the discontinuous dense urban fabric, an explanation could be the combination of a shape parameter (edge density) with a specific thematic urban LULC class (discontinuous dense urban fabric). Edge density is an important spatial index for complexity that relates to many other spatial urban and landscape metrics. It is often used for describing urban form or landscape patterns (Klimek et al., 2014; Schwarz, 2010) and was recently identified as an important link to urban temperature conditions (Weber et al., 2014). The LULC class discontinuous dense urban fabric is commonly found in more central, high density residential urban areas (Baur et al., in press). The synergetic view of both the density of the land cover and the edge density as an urban form indicator describes a city in terms of its building density. It includes the degree of soil sealing, complexity of the urban fabric, as well as indirectly the degree of fragmentation of open and green areas (European Environment Agency and Meirich, 2011). Thus, it allows more detailed analyses of the compactness of inner-urban areas than the variable population density. The addressed compact inner-urban areas provide the highest demand for public transportation, which could be increased by the right incentives to further reduce GHG emission from individual transportation (Creutzig et al., 2012; Eriksson et al., 2008; Tourism&Transport Forum T, 2011).

With household configuration and urban form (regarding density and complexity) being important influences, potential policies to reduce GHG emission should be discussed that address these two drivers. However, politically addressing decreasing numbers of family households and an increasing amount of smaller households is a difficult task. In contrast to spatial measures, it is neither easy nor a short-term action to control socioeconomic properties of residents. A possibility might be the creation of incentives for sharing living space. Therefore, the process of population aging and the increase of elderly households (Długosz, 2011) might show an increasing potential for intergenerational living, with beneficial effects for the young and the elderly (4Children, 2011; Kneale and Bamford, 2012; Gouvernement du Québec, 2014). Further incentives might focus on supporting young families in cities, such as by raising social benefits (child allowance), providing adequate childcare or enabling more flexible working conditions to increase birth rates and household sizes (Bryant, 2008; European Union, 2014).

With regard to the importance of an increased edge density of discontinuous dense urban fabric, policy control might be easier than influencing the socioeconomic–demographic variable household size. Hence, the concept of compact cities should be especially considered when deciding on new zoning maps to reduce energy consumption and GHG emissions (Norman et al., 2006; Lee and Lee, 2014). In this context, policies that aim at strengthening “green belts” around cities should also be investigated (Campaign to Protect Rural England et al., 2010; Smith, 2014). In this way, the prevailing problem of urban sprawl (Baur et al., in press) could be controlled, which has been the case for American (El Nasser and Overberg, 2001; Ewing et al., 2007; Schneider and Woodcock, 2008), Chinese (Deng and Huang, 2004; Feng and Li, 2012), as well as for EU cities (Baur et al., in press; European Environment Agency, 2006; RWI et al., 2010). However, when incentivizing more compact urban development, policy makers and urban planners must also carefully consider social and economic consequences (Breheny, 1995) and possible influences from increasing temperature and precipitation extremes that are predicted to result from future climatic changes (Doick et al., 2014; IPCC, 2014a; Warhurst et al., 2014).

Moreover, whereas direct emission sources (such as electricity production or travel demands) are already under investigation, activities causing indirect emissions are mostly yet to be addressed on the national level. Thus, policy options must be derived that focus on reducing indirect residential GHG emissions. As also stated in Section 4, this requires further specific research. Nevertheless, current findings point at first focus areas: GHG intensive services and recreational activities, including the use of electronic consumer goods and leisure travel (Jackson and Papathanasopoulou, 2008; Ala-Mantila et al., 2014).

By considering both the socioeconomic–demographic (household size) and the spatial (edge density of discontinuous dense urban fabric) dimensions, it is possible to explain 86% of the total variation in the analyzed GHG emissions. This underlines the high importance of both variables and reveals concurrently that there are further influences to tell the full story of GHG emissions. In this context, the wealth of urban residents might be considered in particular, assuming that increasing wealth correlates with higher GHG emissions per capita (Baur et al., 2013; Kennedy et al., 2009a). Also, residents' specific transportation habits are found to directly affect urban GHG emissions (Creutzig et al., 2012). Therefore, a city's modal split and possibilities for enhanced low-carbon transportation should also be investigated. Furthermore, urban population density is assumed to affect GHG emissions per capita (Baur et al., 2013; Kenworthy and Laube, 1996; Newman and Kenworthy, 1989). Because the final variable edge density of the discontinuous dense urban fabric is found to correlate with population density in the analyzed cities, this parameter is only indirectly covered by the presented analysis. Therefore, future research should also further investigate the assumed impact on GHG emissions. Another element that needs to be considered in future studies is the age of the population. This is especially relevant when considering that elderly people have specific needs, for example, in terms of transportation demand or endurance of climatic extremes (Patz et al., 2014), and when recognizing that Europe's population is concurrently continuously aging (Długosz, 2011).

A critical point of this study refers to the application of the reported GHG emission values, which are generally modeled instead of measured, often (but non-exclusively) with the online tool “Ecoregion” (ECOSPEED AG, 2012). Although the authors tried to verify the analyzed emission inventories, this represents an uncertainty in terms of quality and comparability of the reported values. The results further demonstrate the significant direct effect of electricity GHG emissions (related to a city's energy mix) on urban GHG emissions (Kennedy et al., 2009a). Assuming that urban mixes are equal to national mixes and that generally 29.39% of the urban GHG emissions come from electricity production (The Shift Project, 2012), an integrated correction method has been developed. Despite this approach, strong regional influences were still observable (e.g., for the French and Swedish cities). This indicates that the presented simplified, EU-wide approach might not be precise enough to fully capture the respective energy peculiarities of individual urban areas — especially when strongly diverging from the EU average. With global shifts towards more renewable energy sources and thus, higher shares of electricity consumption for final energy uses such as heating or transport, this emission driver deserves close attention (IPCC, 2014b) when comparing international GHG data. For this reason, a more thorough way of handling the identified influence should be developed.

In the end, an important advantage of the introduced GHG estimation approach lies in its simplicity. Thus, being easy-to apply, it supports cities in including measures to control the identified GHG drivers in future development plans, and thus, foster comprehensive climate resilience (considering mitigation and adaptation). However, if emissions are to be more thoroughly modeled, further influences should be included and possible non-linear interactions need to be considered.

4. Conclusions and outlook

The initial hypothesis was that only a few socioeconomic and spatial parameters are required to estimate urban GHG emissions in EU cities. To validate this assumption, a multiple linear model has been calculated including the parameters that were previously identified as crucial urban GHG emission drivers. The results show that information on the household size and the edge densities of the discontinuous dense urban fabric are satisfactory to enable GHG emission estimates for a variety of European cities. In this process, it was found that the increase of both drivers reduces the total GHG emissions per capita.

The model reveals an interesting leverage point for policy makers and urban planners in making their cities more climate-friendly. According to our findings, future policy making should address current trends in household configuration with the aim to support the increase of household sizes. Furthermore, smartly scattered (discontinuous) dense urban structures should be promoted and thus, urban sprawling counteracted. The effectiveness of such policies for a possible reduction of per capita urban GHG emissions can be easily tested with the introduced model.

For the development of expedient policies, further research need to also focus on other aspects that indirectly influence residential GHG emissions per capita, such as human behavior and activities (Minx et al., 2013), as already identified for the “recreation and leisure” sector (Druckman and Jackson, 2009; Ala-Mantila et al., 2014). Indirect GHG emissions might also be influenced by the degree of urbanity which is related to increasing service demands, and thus higher indirect GHG emissions per capita (Ala-Mantila et al., 2014). Another aspect are regional or national decisions which directly influence GHG emission per capita, such as the national electricity mix (Jackson and Papathanasopoulou, 2008). Reducing the emissions of comparable extensive activities must be prioritized for future development plans.

In the end, the introduced model represents a practical approach to estimate the GHG emissions of European cities. Its simplicity, caused by linear relationships between only two variables and the urban GHG emissions per capita (assuming comparable electricity CO_2 intensities), makes it easy to reproduce. By using standardized spatial and demographic data, both variables can be objectively assessed and spatial as well as socioeconomic urban properties can be taken into account. Thus, the model can be used to help cities investigating the importance of the identified GHG emission drivers or derive best practice examples for future development plans and comprehensive climate resilience strategies. However, if more city-specific urban GHG emissions are to be modeled, a more complex approach with additional variables (e.g., climatic conditions, personal purchasing power) and other statistical relationships is needed. Also, varying GHG intensities of different national or regional electricity mixes should be considered.

Appendix A

Table A.1

List of analyzed European cities (sorted alphabetically) and their reported annual total CO_2eq emissions (t/capita scope 1 + 2 and upstream emissions for electricity generation) as well as a corrected version which accounts for varying electricity production methods (CO_2eq-c emissions). Also, the introduced modeled GHG emissions are shown (CO_2eq-m), which result from Eq. (1). The population sizes of the cities under investigation range from 88,000 to 7,668,300 inhabitants. Cities numbered from E1–E10 and marked with an "*" were used for validating the developed model. Socioeconomic data from Eurostat (2011), spatial data from European Commission (2011).

#	City	Country	Population size (persons in tsd)	Household size (person per household)	Edge density of discontinuous dense urban fabric	CO_2eq emissions (t/capita)	CO_2eq-c emissions (t/capita)	CO_2eq-m emissions (t/capita)
1	Aberdeen	UK	210.4	2.1	0.004	7.7	10.26	8.19
2	Augsburg	Germany	263.313	1.89	0.004	9.69	12.61	11.16
3	Belfast	UK	268.3	2.36	0.008	7.7	10.26	5.34
4	Birmingham	UK	1019.2	2.45	0.010	5.4	7.20	4.67
5	Bologna	Italy	372.256	1.88	0.003	11.1	14.71	11.81
6	Bremen	Germany	547.36	1.84	0.005	17.06	22.20	10.4
7	Bristol	UK	426.1	2.27	0.010	4.7	6.26	5.38
E1	Brno*	Czech Republic	370.592	2.42	0.003	6.43	7.44	7.83
8	Cambridge	UK	118.7	2.27	0.004	5.8	7.73	7.55
E2	Cardiff*	UK	330.5	2.47	0.006	6.3	8.40	5.34
9	Cologne	Germany	995.420	1.88	0.004	10.09	13.13	10.4
10	Coventry	UK	310.5	2.37	0.008	5.2	6.93	5.35
11	Derry	UK	109.1	2.77	0.002	6.9	9.20	6.31
E3	Dresden*	Germany	512.234	1.83	0.004	10.17	13.24	10.87
12	Edinburgh	UK	471.7	2.1	0.004	6.1	8.13	8.18
13	Essen	Germany	579.759	1.89	0.007	10.75	13.99	8.67
14	Exeter	UK	118.5	2.23	0.009	4.8	6.40	5.69
15	Frankfurt (Main)	Germany	664.838	1.85	0.003	12.79	16.64	11.54
16	Freiburg (Breisgau)	Germany	219.665	2.07	0.002	7.97	10.37	10.3
17	Glasgow	UK	584.2	2.04	0.009	8.8	11.73	6.76
18	Hamburg	Germany	1772.100	1.82	0.005	9.12	11.87	10.34
19	Helsinki	Finland	549	1.88	0.002	6.01	12.31	8.27
20	Joenkoeping	Sweden	125.154	2.1	1.95E-05	3.19	64.76	2.96
21	Kingston (u.Hull)	UK	261.100	2.3	0.016	5.95	7.93	4.58
22	Leeds	UK	779.3	2.31	0.006	5.5	7.33	6.19
23	Leicester	UK	303.8	2.46	0.009	5.8	7.73	4.83
24	Lincoln	UK	88	2.3	0.007	5.1	6.80	6.03
25	Liverpool	UK	441.1	2.1	0.014	5.6	7.46	5.59
26	London	UK	7668.3	2.36	0.011	6.02	8.02	4.84
E4	Madrid*	Spain	3213.271	2.71	0.002	6.9	13.24	5.30
27	Mainz	Germany	197.623	1.9	0.005	8.5	11.06	9.96
E5	Málaga*	Spain	566.447	3.06	0.001	4.89	7.46	6.35
E6	Manchester*	UK	473.2	2.35	0.012	5.6	7.46	4.78
28	Naples	Italy	973.132	2.58	0.005	4	5.30	5.43
E7	Nantes*	France	579.131	2.16	0.004	4.79	33.99	1.44
29	Newcastle (u. Tyne)	UK	277.8	2.27	0.010	6.1	8.13	5.39
30	Nottingham	UK	296.6	2.21	0.013	5.4	7.20	5.29
31	Nuremberg	Germany	503.638	1.92	0.005	7.4	9.63	9.38
32	Oerebro	Sweden	132.277	1.85	4.73E-05	4.6	93.38	2.83
33	Oulu	Finland	131.585	2	0.0001	13.6	27.85	15.98
E8	Paris*	France	2181.374	1.88	0.001	5.2	36.9	3.4
34	Portsmouth	UK	199.4	2.3	0.013	5.4	7.20	4.88
E9	Prague*	Czech Republic	1233.211	2.27	0.004	7.85	9.08	8.23
E10	Regensburg*	Germany	133.525	1.76	0.005	9.3	12.10	11.10
35	Sheffield	UK	539.8	2.37	0.002	5.7	7.60	8.23
36	Stoke on trent	UK	239.3	2.26	0.010	5.8	7.73	5.43
37	Stuttgart	Germany	600.068	1.92	0.006	8.42	10.95	9.15
38	Turin	Italy	908.263	2.04	0.003	9.7	12.85	10.47
39	Venice	Italy	268.993	2.07	0.003	10	13.25	9.69
40	Vienna	Austria	1674.909	2.01	0.003	5.19	12.74	5.25
41	Wiesbaden	Germany	276.742	1.98	0.003	11.5	14.96	10.12
42	Wolverhampton	UK	238.1	2.38	0.014	5.4	7.20	4.45
43	Worcester	UK	93.9	2.31	0.009	5.3	7.06	5.41
44	Wrexham	UK	132.7	2.41	0.001	10	13.33	9.7

Table A.2
List and description of all socioeconomic parameters, as well as all LULC classes and spatial parameters that were investigated for modeling urban GHG emissions (spatial data ordered alphabetically according to LULC class). Taken from (Baur et al., in press). Note, spatial parameters were only chosen that showed very high significance (p-value < 0.001; $R^2 > 0.4$) and that were available for >50% of the cities under analyses. Parameters marked with an (*) were identified as truly independent (Section 2.2) and were utilized for the development of the final regression model. For all LULC classes: Minimum mapping unit (MinMU): 0.25 ha; Minimum width: 10 m (if not stated otherwise).
Socioeconomic data from Eurostat (2011); spatial data from European Commission (2011) and LULC class descriptions from European Environment Agency and Meirich (2011).

#	Socioeconomic Parameter	Description
1	**Household size**	**Household size*** Presents the average amount of household members [residents/household]
2	**Population density**	**Population Density*** Is calculated from the total urban population size and the total city area[residents/km^2]
	LULC Class	**Spatial parameter**
3–4	**Discontinuous dense urban fabric** Average degree of soil sealing: >50–80% Residential buildings, roads and other artificially surfaced areas.	**Edge density*** ED accounts for the total edge length relative to the total urban area. Higher ED values indicate more rugged (=complex) patches. **NumP/km^2*** NumP/km^2 presents the average number of urban patches per km^2.
5–6	**Discontinuous very low density urban fabric** Average degree of soil sealing: <10% Residential buildings, roads and other artificially surfaced areas. The vegetated areas are predominant, but the land is not dedicated to forestry or agriculture. Example: exclusive residential areas with large gardens.	**Max. distance*** The maximum spatial extent [m] of the LULC class from the city center. **NumP** NumP represents the average number of urban patches.
7	**Forests** MinMU: 1 ha Ground coverage of tree canopy > 30%; tree height > 5 m Including • Bushes and shrubs at the fringe of the forest • Plantations (*Populus* plantations, Christmas trees) • Regeneration/re-colonization: clear cuts, new forest Not including forests within urban areas and/or subject to high human pressure.	**CA** CA presents the total size of the LULC class (sum of all LULC patches) [km^2].
8	**Mineral extraction and dump sites** • Open pit extraction sites (sand, quarries) including water surface, if < MinMU, open-cast mines, inland salinas, oil and gas fields • Their protecting dikes and/or vegetation belts and associated land such as service areas, storage depots • Public, industrial or mine dump sites, raw or liquid wastes, legal or illegal, their protecting dikes and/or vegetation belts and associated land such as service areas.	**Max. distance*** The maximum spatial extent [m] of the LULC class from the city center.
9	**Other roads and associated land** Roads, crossings, intersections and parking areas, including roundabouts and sealed areas with "road surface".	**hotspot distance*** Specific distance [m] between the hotspot (max. relative amount of a LULC class in a certain distance from the city center) and the urban center.
10	**Water** MinMU: 1 ha All water bodies and water courses are considered as long as they exceed an area of 1ha. Including • Sea, lakes, reservoirs, canals • Fish ponds (natural, artificial) (ponds with distance < 10 m are mapped together) • Rivers, including channeled rivers and seasonal rivers (if course is visible in data) Not including shallow water areas covered with reed.	**CA** CA presents the total size of the LULC class (sum of all LULC patches) [km^2].

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Part V

Synthesis

In the first three Chapters of this Part the main research results are summarized with regard to the specific research hypotheses (Chapter I-3). More precise information about the particular results can be found in the respective research publications (Parts II - IV), and conclusions are drawn in Chapter V-5 of this Part.

The fourth Chapter provides further information on the applicability and potential challenges of the research outcomes (e.g., related to the data used or the methodologies applied). Considering that the results may be utilized to identify urban GHG mitigation possibilities, it is also discussed whether the application of such mitigation actions would be hampered by cities' future needs for local climate adaptation (Chapter V-4.3).

V-1 The socioeconomic drivers of urban GHG emissions - Research hypothesis I -

It was hypothesized that there are certain socioeconomic characteristics of a city's population that specifically influence the overall urban GHG emissions. In particular, population density was expected to strongly correlate with emissions, specifically for transport.

By analyzing EU cities, it can be confirmed that socioeconomic urban attributes affect a city's overall GHG emissions. However, the role of population density is less clear than it was initially expected. Whereas other research found a significant influence on transport or total urban GHG emissions (e.g., for cities world-wide), this cannot be confirmed for continental data samples (Asia, Europe, South America). Only in North-American cities, which are known to be very "car-friendly", is population density shown to correlate with transport emissions (Part II). For EU cities, a statistically relevant influence on either transport or overall urban GHG emissions can only be observed (although not very strongly), when data are analyzed on a national basis (for example shown in Figure 2 in Part II).

In this context, it was revealed that there are other important socioeconomic influences that should be taken into account when analyzing total urban GHG emissions. In particular, the emissions of EU cities are significantly affected by absolute household size[15] (Figure 4 in Part II) and, to a lesser extent, the personal wealth of residents[16] (Figure 5 in Part II), both of which describe lifestyle habits of citizens. Increasing household sizes could lead to reduced GHG emissions overall. This parameter also affects such factors as LULC patterns related to the demand for living space (Buzar et al., 2005; Haase et al., 2013; Lauf et al., 2012), or the household-related energy consumption patterns (Wei et al., 2014). Thus, it is considered for further discussion in Chapter V-5.

In contrast, increasing wealth is observed to result in higher emissions. However,

[15] Number of inhabitants per household.

[16] Represented by personal purchasing power.

this effect is less strongly pronounced in the analyzed GHG data (particularly when considering varying electricity emissions). A possible explanation is that wealth-driven GHG influences are found to mostly relate to indirect GHG emissions, such as those from consumption patterns or leisure activities (Ala-Mantila et al., 2014; Druckman and Jackson, 2009; Minx et al., 2013). As the analyzed GHG data do not fully cover such indirect GHG emissions (only scope 1 and 2 emissions), a wealth-related effect is less detectable, especially for relatively income-homogenous EU cities (compared to other global cities).

Overall, the research conducted on various EU (and non-EU) cities reveals that any analysis of urban GHG emissions should be planned carefully. In particular, the specific scope of analysis should be clarified and potential challenges need to be considered. Additionally, the analysis of GHG emission data is greatly strengthened by controlling for varying electricity CO_2 emissions and by differentiating between different city sizes (Part II).

V-2 The spatial drivers of urban GHG emissions
- Research hypothesis II -

In addition to other influences, specific urban spatial structures were also expected to affect a city's total GHG emissions. In particular, density-related characteristics and the intra-urban composition and distribution of various LULC classes were considered relevant.

Investigations of important landscape metrics and multiple LULC classes substantiated these assumptions and identified many significant correlations between spatial urban characteristics and GHG emissions (Table 2 in Appendix of Part III). In particular, high-density urban areas with a very fragmented LULC composition[17] are found to significantly correlate with lower GHG emissions per capita (Figure 3 in Part III). As this spatial indicator further strongly correlated with the socioeconomic variable "population density"[18] that was not shown to be significantly influencing GHG emissions, its precise role for urban GHG emission should be further discussed (Chapter V-5). In contrast, low-density urban areas (e.g., exclusive residential areas with large gardens or natural areas) strongly relate to higher GHG emissions.

Further results show that a city's specific urban LULC pattern (including the distribution and composition of LULC) influences its GHG emissions. Unlike the previous findings regarding the impact of density, characteristics of the LULC pattern (e.g., the number of relevant LULC classes) more strongly depend on the particular size and growth pattern of a city. As a consequence, only relative distance parameters (relative to the total city size) were found to correlate with emissions. Specific examples for medium-sized cities are shown in Figure 4 in the Appendix of Part III.

In addition to density-related correlations with urban GHG emissions and influences from LULC patterns, the complexity of the overall shape of a city ($PUSH_C$ parameter) was also found to affect its GHG emissions (Figure 5 in the Appendix of Part III). Thus, the more frayed a city's expansion into surrounding areas is, the higher its overall

[17] High edge density (ED) of the discontinuous dense urban fabric (DDUF).

[18] Pearson correlation coefficient: 0.8; bivariate regression analysis: R^2= 0.63 and p-values < 0.001).

emissions are (depending on the specific urban size and population growth pattern; e.g., the strongest effect for fast growing urban areas).

In summary, the results show that there are specific spatial urban characteristics that correlate with GHG emissions. In particular, spatial properties that describe the problem of urban sprawl (low-density urban areas, specifically in urban outskirts, and a frayed expansion into the surrounding area) are found to correlate with increased urban emissions. In contrast, more compact inner-urban areas (shown by high ED of DDUF) can lead to lower emissions per capita. It needs to be mentioned that the LULC class DDUF does not represent fully sealed urban areas, as the LULC class CUF would have done. Further discussions on this possibly important distinction are presented in Chapter V-4.3.5.

V-3 Limited requirements for estimating urban GHG emissions - Research hypothesis III -

It was assumed that there are only a very limited number or socioeconomic and spatial parameters required for estimating urban GHG emissions. With regard to the identification of various potential GHG influences (Parts II and III), it is preferable to focus on the most important GHG drivers to find an straightforward way to estimate emissions.

To this end, research was conducted on all previously identified significant GHG emission influences, while keeping in mind the findings about a potential bias from varying electricity CO_2 intensities (Part IV). Analyses were focused on all EU cities and not on specific city archetypes[19] to gain more general insights into important GHG drivers over a wider scope of cities.

The research shows that it is possible to statistically reduce the total number of GHG influences to the socioeconomic parameter "household size" (HH) and the spatial parameter "edge density of the discontinuous dense urban fabric" (ED DDUF). Thus, research hypothesis III (Chapter I-3) can be confirmed. The identified main influences can further be combined into a multiple linear regression model (Algorithm V-1)[20] that can be used to explain 86% of the total GHG emissions (Table V-1)[21].

Algorithm V-1 Final multiple regression model for estimating GHG emissions in EU cities. δ represents the differences between nations' electricity CO_2 intensities and is used for re-transforming corrected GHG emissions to reported values

$$\mathrm{CO_2\ eq\text{-}m} = 10^{0.89-1.87\times\lg(HH)-0.32\times\lg(EDDDUF)} \times \delta$$

Both variables are logarithmically correlated to emissions. Thus, the overall model also scales logarithmically with urban GHG emissions (shown as linear regression plane in FigureV-1[22]).

[19] As done for the detailed identification of previous emission determinants in Parts II and III.

[20] Algorithm V-1 and Table V-1 have already been published in Part III.

[21] To obtain the parameter statistics of Table V-1, it is necessary to calculate Algorithm V-1 for the

Table V-1: Statistics of the final multiple regression model, showing a strong influence of household size (HH) and edge density of the discontinuous dense urban fabric (ED DDUF) on the corrected GHG emissions of EU urbanites (CO_2 eq-c)

Variables	Coefficients	Std. error	P-values (F-statistics)
Intercept	0.89267	0.13417	5.10e-08 ***
lg (HH)	-1.87292	0.31583	5.44e-07 ***
lg (ED DDUF)	-0.31632	0.02465	6.03e-16 ***

*Significance: '***' = p-value <0.001*

Adjusted R-squared: 0.86, **p-value:** < 2.2e-16, **F-statistic:** 131.2 on 2 and 41 DF

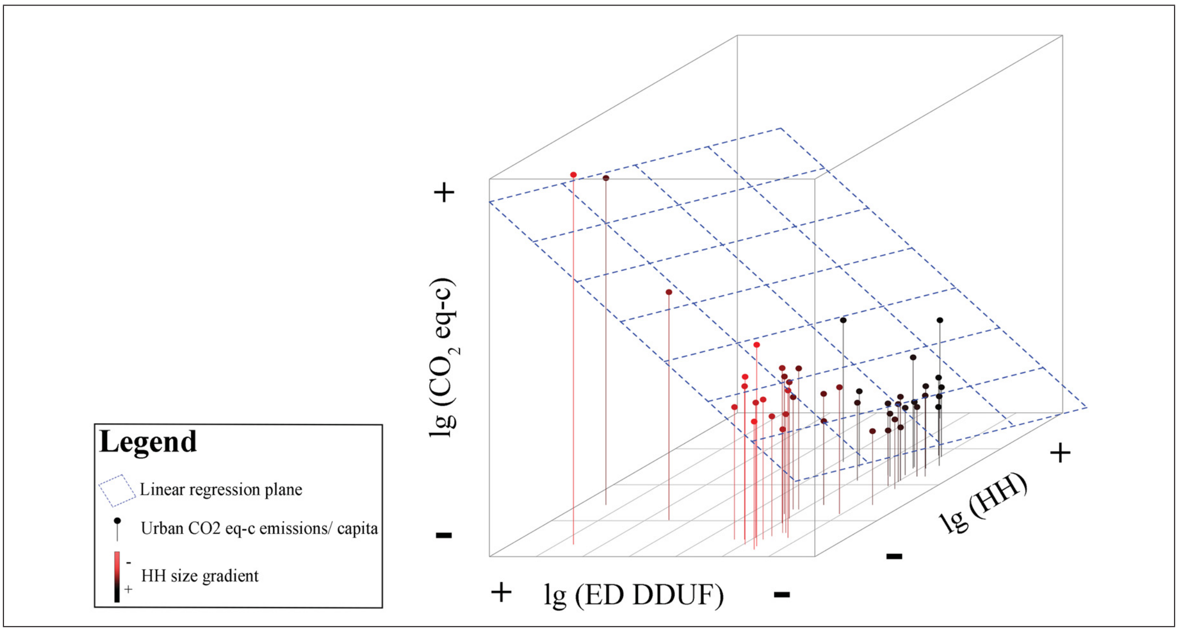

Figure V-1: Final linear regression model, showing the combined influence of household size (HH) and edge density of the discontinuous dense urban fabric (ED DDUF) on the corrected GHG emissions of EU urbanites

To verify that the detection of these influences does not depend on the introduced correction approach for varying electricity emissions, the importance of both parameters was investigated both for the original GHG emission data and for analyzing further cities. Therefore, the parameter δ was used for re-transforming the GHG emission data to its original state (as reported by the cities). The results prove that both parameters are important GHG emissions drivers, including when the original GHG data (Figure 1 in Part IV) are used, as well as when analyzing additional cities (Figure 3 in Part IV).

corrected GHG emissions (omitting δ).

[22] Figure V-1 illustrates the overall modeled influence of HH and ED DDUF on GHG emissions in EU cities. More detailed information (e.g., about the specific urban emissions) can be found in Figure 1 in Part IV.

V-4 Applicability and challenges

By analyzing the GHG emissions of EU cities, the most significant socioeconomic and spatial GHG drivers were identified. It was further shown that a multiple linear regression model with the two variables “household size” and “edge density of the LULC class discontinuous dense urban fabric” can be used for estimating the GHG emissions of EU cities.

The following Sections provide further insights into possible future applications of the presented findings and potential challenges that might relate to data, methodologies or cities’ future adaptation needs related to climate change (**CC**) impacts.

V-4.1 Scope of analysis

As presented in Figure I-1, cities in various EU countries were included in the presented analyses. The actual evenness of the city distribution depends on the analyzed data and thus on the underlying specific urban characteristics. Hence, the scopes of analysis slightly varied between the different research projects (Parts II-IV). The most determining factor was the availability of sound and comparable information about urban GHG emissions (Chapter V-4.1). For these cities, data from Eurostat’s UAT project was utilized for the analysis of socioeconomic GHG drivers of 62 EU cities (Part II). For the analysis of spatial urban GHG influences (Part III), data from EU’s UA project was used, providing uniform spatial LULC data for 52 (of the total 62) EU cities. Concerning the final research Part (Part IV), data from both data sources were required, which was possible for 44 of the 62 original cities.

When limited to the availability of applicable data, the entire dataset included a comparably large number of cities in Germany and the UK. Although German cities were found to be hotspots of urban sprawl in the EU (Arribas-Bel et al., 2011), additional cities for confirming the final research findings were selected in order to improve the EU-wide distribution (Part IV). Therefore, for example, cities from Spain, France or the Czech Republic were selected, broadening the geographical scope of analysis.

In general, the scope of analysis allowed for a comprehensive investigation of GHG emissions in EU cities. The analyzed dataset included cities of various nations and, in contrast to former studies (Chapter I-2), different city sizes. Although the final dataset included a comparably large share of medium-sized cities (100,000-500,000 inhabitants)[23], the overall data coverage represented the EU urban situation well (United Nations, 2014). Analyzing this multinational dataset, it is also possible to identify specific GHG influences, including those that originate from national peculiarities (e.g., urban design preferences or energy productions) or from specific challenges and opportunities related to a city's size (Part II).

Also with regard to data requirements, the decision to focus on EU cities positively affects the research project in multiple ways:

1. Strong EU environmental legislation fosters sustainable development (Reckien et al., 2014), leading to a push for nations and cities to become more climate-friendly. Consequently, various public and commercial initiatives are now advancing low-carbon developments (e.g., application of GHG inventory tools such as ECORegion[24]). Thus, focusing on EU cities eased the collection of comparable urban GHG data, particularly considering that GHG emissions were the most limiting factor for the scale of analysis.
2. The cross-national EU data service Eurostat provided a useful database for comparable socioeconomic and spatial data, because the same methodologies were applied for all EU countries. This provided an important prerequisite for thorough statistical analyses of all potential GHG influences, despite a slight divergence in data acquisition dates (more information in can be found in Chapter V-4.2).

Since only core city areas as defined by administrative city boundaries were analyzed, the LUZ was necessarily excluded. This impeded an in-depth analysis of cities' linkages to their hinterland. In some cases the analysis of LUZ is more appropriate, particularly when investigating commuting patterns for those who work and dwell in different zones[25]. However, using LUZ data for an analysis of various international cities is also more error-prone. Concerning the specific relevance of comparable data, the availability of useful cross-national LUZ information was very limited at the time of research, including the necessity for detailed commuting data for defining the LUZ. Thus, there would be distinctive methodological differences between nations, on which urban surroundings to include. These methodologically differences could have very biasing effects on for example, the analysis of LULC compositions and distributions. It was only in 2012 when a first approach was introduced by the EU Commission to more uniformly define the LUZ and generate the corresponding data (European Commission, 2012), although only for EU cities.

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[23] 58% in the dataset utilized for Part (II).

[24] ECOSPEED AG (2014).

[25] As shown for example, by Nielsen et al. (2005).

The analysis of only the urban core areas instead helped to avoid national (or even regional) distortions from varying LUZ definitions. Moreover, administrative city borders are more clearly defined and usually known to city authorities, who also calculate urban statistics such as population size or density. Since the socioeconomic data were calculated using the administrative urban boundaries (Georgi, 2012), the focus on the core city areas allows the datasets (GHG, socioeconomic and spatial data) to be comparable. While the geographical area is smaller without the LUZ, this delineation allows for the consideration of the most important urban activities, processes and the majority of the urban population (European Commission, 2015), albeit not the entire urban population (European Commission, 2012)[26].

Regardless of the present advantages in analyzing EU cities, expanding the scope of the analysis beyond EU borders and including further emissions (e.g., investigating LUZs) is expected to result in additional insights into demographic and behavioral emission influences (further discussions follow in Chapter V-5).

V-4.2 Data and methodologies of analysis

Quantitative analyses always include specific strengths and weaknesses, related to the utilized data and methodologies. The following Subsections highlight the most important considerations in this regard, by focusing first on the original data and subsequently on the applied methodologies (calculation and modification of data).

V-4.2.1 Data

As highlighted before, particular efforts were made to use a comprehensive set of comparable data (e.g., Chapter I-5.2.1 in Part I). By limiting the scope of analysis to only cities in the EU (Chapter V-4.1), it was possible to utilize data from the EU wide statistical service Eurostat. The socioeconomic data and GHG data were mainly assessed for the period 2007-2009 (Part II) and the spatial data were referenced to the year 2006 (+-1 year). Although these acquisition dates do not completely coincide, the information is considered to be comparable because extensive changes in the overall urban layout (specifically concerning spatial structures) are not assumed for the maximum offset time of 5 years (Part III).

[26] Administrative city boundaries may go beyond built-up urban areas, including also agricultural and natural sites (illustrated in Chapter VI-1 in the Appendix).

Concerning the analyzed GHG data, care was taken that the emission dataset included only CO_2 eq emission data that were modeled with the same methodological approach[27] and that the equivalent emission sources were included[28]. However, there are also specific limitations with certain data characteristics. For example, a detection of GHG influences from climatic variables (e.g., heating or cooling degree days) was restricted by cities' preceding data corrections for different climatic conditions. Therefore, the following points could be considered for the further development of the GHG emission dataset:

1. The collected GHG emission values do not reflect real CO_2 measurements, but instead are often (but non-exclusively) modeled with the online tool ECORegion.
   - Representative measurements (including all relevant emission sources) of urban CO_2 emissions are difficult to obtain. Thus, the modeling of emissions (such as via considering the energy consumption) is a valid approach. However, more clarity in the utilized inventory models can provide a better understanding of the emission data being calculated and reported by cities. Otherwise, this lack of transparency presents an uncertainty in terms of quality and comparability in the GHG data (e.g., regarding the emission sources included).

2. The scope of the included GHG should be expanded with regard to emissions and emission sources.
   - On the one hand, a greater number of GHG could be considered.
     The covered emissions mainly represent CO_2 eq emissions, which have been shown to be the most important emissions to curb (Chapter I-5.2.1). However, the consideration of additional GHG would provide a more comprehensive picture of emissions. As indicated in Figure I-3, future urban emission inventories might therefore also consider CH_4, HFCs, N_2O, PFCs, and SF_6 emissions.
   - On the other hand, further urban emission sources could be included.
     Therefore, in addition to the already covered scope 1 and 2 emissions, scope 3 urban GHG emissions might also be considered in order to address indirect emission sources (e.g., from manufactured goods from outside the city or from waste disposal). This could strongly improve the overall representation of cities' real GHG situations. In order to do so, however, most widely-used GHG inventory tools would have to be adapted and larger amounts of input data would be required from cities.

[27] Based on the final energy consumption, and corrected for different climatic conditions.
[28] Scope 1 and scope 2 emissions and upstream emissions for energy production.

A stronger commitment from EU nations to enhance CC mitigation (e.g., adopting stricter environmental regulations) could push cities to become more climate-friendly. This could initiate the development of incentives to realize these improvements.

V-4.2.2 Methodologies

Investigating the main research hypotheses required two separate methodological workflows. Both are discussed separately in the subsequent paragraphs:

1. Calculation and modification of data.
2. Statistical analyses of potential socioeconomic and spatial urban GHG influences.

Calculation and modification of data

As stated previously, uniform data are needed for analyzing the GHG emissions of the international cities (e.g., Chapter V-4.2.1). Therefore, adequate datasets were used to determine possible socioeconomic and spatial urban emission influences (both compiled by the EU). While socioeconomic parameters were already available (such as the absolute number of persons per household), the spatial parameters had to be calculated. This was performed in the ArcGIS software, with the applied calculation processes shown in Figure I-6 and Figure I-7.

Concerning the intra-urban LULC composition, various landscape metrics were calculated for both the entire urban area and for each UA LULC class. The resulting dataset could then be used to not only identify possible city-wide, or LULC class-specific patterns that correlate with urban GHG emissions, but also to verify former findings about the general importance of specific landscape metrics such as the edge density (Schwarz, 2010; Webb et al., 2011).

With regard to the investigation of intra-urban LULC distributions, a universally valid approach to determine the central urban areas had to be developed as a prerequisite. As these areas are related to important urban activities and processes, they are expected to be relevant for analyses of urban GHG emissions (Chapter I-2). The calculation of the median center of the UA LULC class “Continuous Urban Fabrics” in ArcGIS (Chapter I-5.3.2) resulted in usable results for all urban areas. As an example, Figure I-5 presents the calculated urban center of London and its real-life representation (map and picture). Compared to descriptions of this area type (European Environment Agency and Meirich, 2011; Hartshorn, 1991), the developed approach uniformly detects the central urban areas for the planned investigations. Applying these findings, analyses of LULC-distributions were then carried out in both absolute (LULC analysis every 1 km) and, relative terms (LULC analysis every 10% of the maximum city radius), accounting for possible scale effects from varying city sizes. As it turned out, analyses overall benefitted from this process, even when cities were already analyzed with regard to their city size, revealing a more detailed picture of the influence of the specific LULC pattern.

In order to derive the spatial parameter $PUSH_C$, a methodology was developed that describes a measure of the overall complexity of a city's shape. As current knowledge about the effect of city's overall shape or growth pattern on GHG emissions is very limited, this parameter presents an easy-to-calculate spatial metric that can help clarify possible linkages. As the simple underlying model can only provide indicative results, future research should develop this approach further.

Beyond socioeconomic and spatial parameters, initial analyses revealed that the analyzed urban GHG emission data were also influenced by the typical types of national electricity production (Part II). However, no direct correlation was found between the specific national CO_2 intensities of electricity production (in g CO_2 / kWh) and the GHG emissions per capita. As neither the analyzed socioeconomic or spatial characteristics of cities are directly connected to the national electricity production method, its influence on the cities' electricity-related GHG emissions cannot be explained by the investigated parameters, and thus represents an uncertainty in the original dataset.

To account for this bias, an easy approach was introduced to level the varying GHG influence of the national electricity production, which was assumed to affect 29.39% of the overall urban GHG emissions (Chapter I-5.3.2). Therefore, the respective share of the original emissions was divided by its national CO_2 intensity (e.g., Germany: 494g CO_2 / kWh), which resulted in an increase of all emission values (for example shown in Figure I-1). However, this effect was stronger for cities in countries with a less CO_2-intensive electricity production (e.g., Austria, France, Sweden), than for countries that have a more CO_2-intensive electricity production (e.g., Poland, Czech Republic). The final "corrected" GHG emission data were less biased by different electricity CO_2 intensities and thus, more useful for investigating the influences of the analyzed parameters.

Subsequent analyses revealed that this way of leveling the GHG emission data offers not only distinctive strengths, but also weaknesses, considering that the presented calculation tends to disproportionally affect the emissions of cities in countries with comparably low CO_2-intensive electricity production (e.g., using hydro- or nuclear power). Fortunately, this affected only ~8% of the cities (5 of 62 cities, in Austria, France, and Sweden). In order to estimate the overall meaning for the conclusions, other corrections of the electricity influence were also tested (e.g., using specific national deviations from the average EU electricity intensity). However, no other significant results were obtained, which supported the previous conclusions. Furthermore, it might be criticized that the approach generally considers 29.39% of total urban GHG emissions as influenced by the national electricity production. A better, more specific solution would be to use national statistics (regarding power generation) in addition, and thus perform more precise corrections of cities' GHG data. A distinctive asset of the presented correction method is its applicability. Thus, by using publicly available data and a simple correction methodology (Algorithm I-2), it was possible to make total urban GHG emissions analyzable for parameters that are not expected to have specific influences on a city's electricity production.

This is a clear advantage for the presented analyses, in particular concerning the multi-national scope of investigation.

In the end, the importance of minding the role of energy-related GHG emissions can be shown. Future research should consider these remarks and develop the introduced GHG data correction further. Therefore, more national or even city-specific data should be used to improve the analysis of urban peculiarities.

Statistical analyses of potential socioeconomic and spatial urban GHG influences

The socioeconomic and spatial parameters were analyzed separately for their influence on urban GHG emissions per capita. The underlying statistical analyses were done with the statistical software package "R" (R Development Core Team, 2012) and mainly constituted of bivariate linear regression analyses. Multiple linear regression models were also calculated for the analysis of socioeconomic GHG drivers, but could not reveal any additional insights. Therefore, only bivariate linear relationships with GHG emissions were considered for the data-intensive analysis of spatial emission drivers. Using the findings from both socioeconomic and spatial analyses, a set of the most significant GHG influences was identified *(research hypothesis III)*. Therefore, multiple regression models were investigated in order to consider possible interactions between both types of parameters. Specific calculations included not only linear ("household size") but also logarithmic ("lg household size") and mixed (linear and logarithmic) relationships of important variables for GHG emissions. The results confirmed that a multiple linear regression model with variables that are logarithmically related to emissions is most suitable for estimating urban GHG emissions (Table V-2)[29].

The analysis of socioeconomic influences has already shown that city-archetype specific investigations can reveal further emission influences (Part II), so respective analyses were also performed to investigate spatial GHG drivers (Part III), and tested in order to identify the most important GHG influences overall (Part IV). However, due to difficulties identified in the last research Part regarding the statistical analysis of small

[29] Table V-2 still contains three lg-variables. However, the parameter "lg (max.distance of mineral extraction and dump sites)" was removed afterwards in the development of the final regression model (Algorithm V-1) due to insignificant F-statistics).

Table V-2: Comparison of model performance (complexity and explanatory power) of various final multiple statistical model versions (linear, lg, mixed)

Model parameter	Linear variable relations	Lg. variable relations	"Mixed" variable relations
Number of variables	3	3	4
R^2	0.76	0.91	0.83
P-value	<0.001	<0.001	<0.001

sample sizes (e.g., only 13 large cities to analyze the impact of seven, potentially important, input parameters), it was decided to focus the statistical analysis on the overall EU dataset. Considering all possibly important GHG determinants, this was feasible for 44 cities (Table A1 in Part IV).

Both the final focus on linear regression analysis as well as on all EU cities overall can be critically discussed. When considering that urban GHG emissions are influenced by multiple urban processes, their exact calculation might require taking more complex interactions into account (e.g., GHG increasing and decreasing processes). Hence, accurate estimations will probably have to also consider non-linear statistical relationships among GHG determinants, and towards GHG emissions. However, for the main purpose of this research (Chapter I-3), a final linear model is advantageous, because it is easier to understand and reproduce than a non-linear model. The results also show that for the presented scope of analysis, a linear model with logarithmically-related variables outperformed other model types with regard to model complexity and explanatory power (Table V-2).

Concerning the final, non-differentiated analysis of all EU cities (with regard to city size or population dynamics), it can be criticized that this approach ignores specific urban peculiarities that are linked to the city size (Part II). However, as data sample sizes became too small for thorough statistical analyses, research was directed at finding more generally valid GHG drivers rather than city-specific influences, which would have required an in-depth case study of a specific city. Moreover, utilizing the revealed socioeconomic and spatial GHG influences for a more aggregate analysis results in a better general applicability of the conclusions for EU cities (scope of this thesis). This is further supported by the characteristics of the final dataset, which represents the typical urban situation in EU well (United Nations, 2014).

V-4.3 Compatibility with future urban CC adaptation needs

Specific significant GHG influences were identified for EU cities. These influences can be used to estimate urban GHG emissions, but can also be considered when developing effective CC mitigation strategies. In this context, possible policy examples were shown for addressing these GHG drivers (e.g., in Part IV). However, successfully implementing these recommendations requires considering their financial and social feasibility, as well as their compatibility with future CC adaptation needs. As the main focus of this thesis is on cities' interaction with CC, this Section elaborates on the latter aspect. Regarding the financial and social considerations of urban CC actions, there is already a variety of research that analyzes either one or both aspects[30]. In order to check whether the identified urban GHG emission reductions can be incorporated into cities' future CC adaptation strategies, a short literature review was conducted regarding the main CC-induced adaption needs and their respective planning strategies. In the end, a critical evaluation of the identified urban GHG mitigation potentials was done, considering cities' future adaptation needs.

V-4.3.1 The need for CC adaptation

As highlighted in the prelude of this thesis, climatic changes due to anthropogenic GHG emissions are unavoidable. Although the final degree and scope of these changes are less certain (Hallegatte, 2009), there is a scientific consensus that these changes will be highly local, differing across sectors and regions (IPCC, 2014a; The World Bank Group, 2014a). In consideration of the importance of corresponding adaptation strategies, even military institutions are preparing for the implications of shifting climatic conditions (United States Department of Defense, 2014). Overall, impacts are expected in the following key sectors (The World Bank Group, 2014a):

- Heat and drought (including wildfires).
- Glaciers.
- Sea and coast.
- Water (freshwater availability and flooding).
- Forests and biodiversity.
- Food.
- Health.

[30] Refer e.g., to Bulkeley et al. (2014); Gusdorf et al. (2008); IPCC (2014b).

Many of these impacts will affect human beings directly. Examples include worsened weather-related natural disasters, such as heat waves or flash-floods, or rising sea levels that threaten coastal populations in particular (Climate Central, 2014). In addition, indirect implications are expected for all key anthropogenic activities[31]. Wide spread effects are already observable for various ecosystems and with regard to Europe, the retreat of glaciers (Alpine, Scandinavian, and Icelandic), increased forest fires (Portugal, Greece), or changing distributional shifts of marine creatures (zooplankton, fish, seabirds) are just a few examples (IPCC, 2014b).

Regarding possible financial damages, global analyses estimate costs of 70-100 US$ billion annually by 2050, assuming a 2°C warmer world than today (The World Bank Group, 2010). However, as adaptation costs will be very location-specific and distinctive limitations exist for current cost-estimations[32], current financial damage estimates must be considered with care. In general, it is assumed that these numbers may still underestimate the actual costs (Chambwera et al., 2014), and as CC increases, costs and challenges for adaptation are expected to strongly rise (IPCC, 2014a).

The possibilities for addressing these impacts depend on the local context (e.g., the specific vulnerability of the population or the infrastructure) and, according to recommendations of the IPCC in 2014, include the following measures:

- Technological process optimization.
- Information systems to support early warning and proactive planning.
- Integrated natural resources management.
- Financial services, including risk transfer.
- Social, ecological asset and infrastructure development.
- Institutional, educational and behavioral change or reinforcement.
- Reducing basic service deficits, improving housing, and building resilient infrastructure.

Overall, effective strategies and actions should consider co-benefits and opportunities, as well as potential trade-offs and should be implemented within wider strategic development goals and plans (IPCC, 2014a).

[31] For example, rising global mean temperatures might affect oceans and thus, fish populations. This poses a threat to about 1 billion people, mostly in developing countries that rely on fish as the main animal protein source (Marine Stewardship Council, 2014).

[32] E.g., regarding discount rates, non-market benefits and co-benefits, or final CC adaptation requirements.

V-4.3.2 Cities' need for CC adaptation

As cities accommodate the majority of the global population, many CC risks will be concentrated in urban areas (Reckien et al., 2014). These include heat stress, drought, water scarcity, air pollution, extreme precipitation, inland and coastal flooding, and landslides, which all pose risks in urban areas for people, assets, economies, and ecosystems. Particularly at risk are populations that lack essential infrastructure and services or that live in poor-quality housing and exposed areas (IPCC, 2014c). For example, global temperature increases would have significant effects on urban areas (Figure V-2) already having to cope with warmer ambient temperatures related to urban heat island (**UHI**) effects (Su et al., 2012).

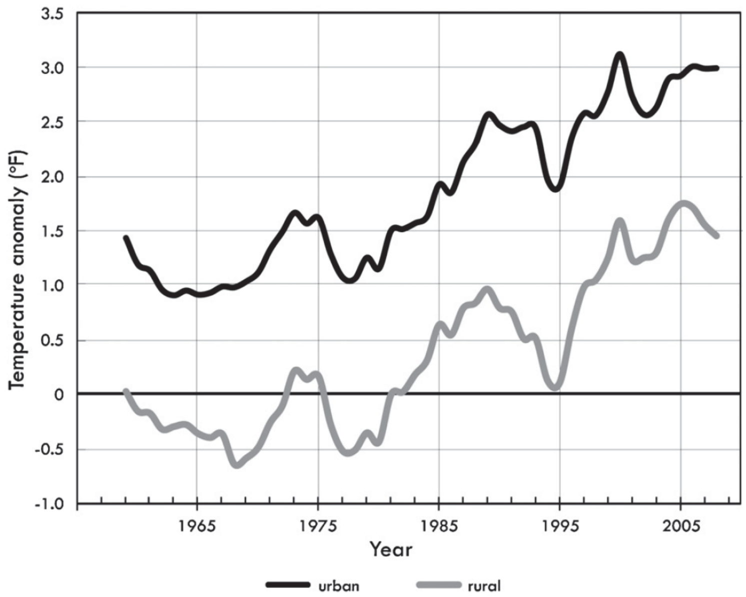

Figure V-2: Temperature increases in 50 US cities compared to rural areas (Stone et al., 2012)

Although the aforementioned possibilities for general adaptation apply, cities require specific measures to address highly regional CC effects (The World Bank Group, 2014a; University of Cambridge Institute for Sustainability Leadership et al., 2014). In addition, large-scale public-private risk reduction initiatives and economic diversification should also be considered (IPCC, 2014a).

V-4.3.3 Most significant CC impacts on and adaptation possibilities of EU cities

While this research is focused on analyzing EU cities, it is also relevant to consider the main EU-specific CC impacts and related adaptation needs. More detailed information about other impacts or further regions can, for example, be found in IPCC (2014a) and in The World Bank Group (2014a).

Heat

As shown in Figure V-2 for US cities, urban areas in the EU are similarly expected to face strong temperature increases due to CC (Stainforth et al., 2013). Although some thermal adaptation by local populations is detectable (Wei et al., 2014), current temperature conditions[33] and future climatic changes[34] are expected to greatly impact the health and well-being of the urban population (Douglas, 2012; IPCC, 2014b; Müller et al., 2014).

Related direct (e.g., respiratory disorders) or indirect health risks (infectious, vector-borne diseases such as “Lyme disease”) are assumed to result in more heat-related fatalities and economic losses, caused by such factors as reduced work capacity. In particular, the elderly, poor, socially-isolated, and those with underlying mental illness are assumed to be at risk (Doick et al., 2014; Patz et al., 2014). For specific sensitivities to heat, local city characteristics are found to be highly important (European Environment Agency, 2012).

Measures are needed to combat UHI effects and prevent further increases of summer heat loads due to CC, particularly for nighttime temperatures (Höppe, 2015). Therefore, most adaptation strategies recommend an increase in natural areas within the urban landscape (Jenerette et al., 2007; Razzaghmanesh et al., 2014), although preferences for urban nature vary between societies[35]. In particular, trees and greenspaces are recognized for their potential to regulate urban air temperatures (Doick et al., 2014; European Environment Agency, 2012). Water bodies are also found to be beneficial for transporting cool air into built-up areas (Müller et al., 2014). However, the effectiveness of both strategies strongly depends on the size, structure and design of the natural area, as well as of the surrounding urban fabric (Doick et al., 2014).

For London it is concluded that urban planners should use small wooded greenspaces (in preference to large open or grassed spaces) and include wider forms of urban greening (including green roofs and cool pavements) in UHI mitigation strategies to ensure effective and widespread cooling[36] (Doick et al., 2014). In contrast, for a German

[33] E.g., in London nighttime temperatures can already be 9°C higher than in surrounding areas (Doick et al., 2014).

[34] More frequent heat waves with increasing number of hotter days and nights are expected.

[35] E.g., in Hong Kong or Singapore urbanites are less keen on having natural spots in their city (Douglas, 2012).

[36] With regard to green roofs, site-specific recommendations for successful set-ups (slope, depth, media-type and species), in particular for dryer climates, can be found in Razzaghmanesh et al. (2014).

city, the creation of park areas (>1ha) with sufficient water supply, and trees that allow for adequate ventilation (tall, isolated, and shade-providing) are recommended. However, small natural sites (e.g., parks with sizes of 0.4 ha) are also found to reduce a population's physiologically equivalent temperature (Müller et al., 2014).

Water stress

Rising temperatures are also directly connected to problems relating to drought. Although there are studies asserting that the expected water stress for global urban populations might be overestimated[37] (McDonald et al., 2014), southern EU regions and cities in particular might face increasing water shortages (Behrens et al., 2010). Reasons include significant reductions in water availability, from both river abstraction and ground water, and an increasing demand for water, not only for domestic usage, but also for irrigation and energy production (IPCC, 2014b; Hessisches Ministerium für Umwelt, Landwirtschaft und Verbraucherschutz und Energie, 2012).

Possible adaptation measures include a widespread application of water-efficient technologies and the development of water saving strategies. Thus for example, crop irrigation should consider highly water-efficient technologies and best practice examples should be used to develop urban and regional integrated water management plans (IPCC, 2014b). Water trading might be also a possibility for water-stressed cities, as well as water recycling or desalinization for coastal areas (IPCC, 2014a).

Flooding

Another important impact of CC, in particular for EU cities, is an increasing risk of flooding, which relates to increasing health challenges (Patz and Grabow, 2014) and economic losses[38] (European Environment Agency, 2012; World Resources Institute, 2015). Reasons include an increasing demand for attenuation storage volume (for reducing the peak flow rate) due to more extreme precipitation patterns, increasing sea levels and peak river discharges (IPCC, 2014b; Warhurst et al., 2014). On the other hand, increasing urbanization is leading to growing rates of land conversion from permeable to impermeable surfaces. This is not only observed on the urban fringe, but also within cities (according to Warhurst et al. (2014) for example, transforming gardens to parking spaces) .

Although flooding events can pose significant risks, available adaptation possibilities and existing experience in flood-protection technologies (e.g., dependable flood barriers and

[37] Water stress estimations might have not accounted for cities' total water infrastructure that extends beyond the urban borders.

[38] For example, in 2013 the flood in Germany caused economic damages of 11.7 billion € (Munich RE, 2014).

flood gates) limit the most serious impacts in the EU. Wetland restoration is another widely acknowledged measure; however, as many areas in the EU are already highly urbanized, the high demand for land related land use conflicts (e.g., with agriculture) pose a barrier to the implementation of this adaptation measure (IPCC, 2014b).

V-4.3.4 A review of current adaptation plans - are cities prepared for climatic change?

In summary, EU cities should take particular consideration of future rising temperatures (and related water stress) and local extreme precipitation events (flooding) for their future urban planning strategies. Keeping these recommendations in mind, a short review of the current urban development plans of 24 German cities was conducted by Donner et al. (in print) to investigate if cities are incorporating future CC adaptation measures into their urban planning.

According to their analysis, current CC-related urban planning in German cities can be summarized by the following characteristics:

1. Whereas almost all cities include measures for reducing GHG emissions, only around 70% of cities address (or at least partially address) adaptation measures to climatic changes.
2. If cities include CC-related adaptation requirements, they are mostly linked to strategies for GHG emission reduction (incl. energy efficiency).
3. In terms of the adaptation-related topics addressed, cities consider "fresh air" (e.g., fresh air corridors), as well as "dealing with heavy rain events" as the most important.
4. Concerning specific adaptation strategies, "green space management" (incl. drip irrigation, changes in design and management of green and public spaces), "tree management" (e.g., heat resistant species), and "green roofs and walls" are preferred measures to counteract future CC impacts.

In general, the findings show that German cities currently have a stronger focus on GHG emission reduction than on preparing for future CC impacts. If specific CC adaptation measures are mentioned, they include the application of "no-regret measures"[39] and mainly address the problem of urban heat, which might already be an issue for some cities (considering UHI effects). Accordingly, their strategies concentrate on urban

[39] "No-regret" measures are activities that yield benefits even in the absence of climate change. For example, controlling leakages in water pipes or maintaining drainage channels (European Commission and European Environment Agency, 2015).

green spaces (also to improve air quality). With regard to an increasing risk of flooding, cities are not particularly concerned ("flood" was also a specific category), although, they address "heavy rain events". However, they neither highlight specific flood-control measures, nor consider "water sensitive urban design-strategies" (Coutts et al., 2012), but seem to rely on increasing open and green areas in response to an increasing demand for attenuation storage volume. A possible explanation can be found in Germany's recent history, where cities had to cope with multiple floods and thus, already developed specific flood-protection strategies.

Similar situations were also found for global cities (Castán Broto and Bulkeley, 2013) and were evident from a recent analysis of 200 EU cities (Reckien et al., 2014). It was concluded that 72% of EU cities still do not have appropriate adaptation plans in place and that no city has an adaptation strategy without a mitigation plan. In general, cities seem to be less aware of the importance of specific CC adaptation strategies (Köferl, 2015). Such would imply the development of thorough adaptation plans (Donner et al., in print), including highly effective measures that, for example, change the albedo of the urban structures to control ambient temperatures. A similar conclusion was found for US cities, where analyses concluded that current CC management policies and action plans may not adequately protect human health[40]. For improving current plans, consideration should be given to adaptation strategies which are multifaceted, include various city levels, and which can become a part of the long-term urban planning processes (Oberlack and Eisenack, 2014; Powell, 2015). Furthermore, a strong linkage to already existing plans (e.g., stormwater management) is recommendable (Bundesministerium für Verkehr Bau und Stadtentwicklung, 2012; Doick et al., 2014; Wernstedt et al., 2014).

V-4.3.5 Are the identified CC mitigation options compatible with EU cities' CC adaptation requirements?

It has been shown that CC will most probably lead to increasing temperatures in EU cities[41]. In addition, local drought events (mostly in the southern EU) or flooding (northern EU) might threaten the urban population. To mitigate both risks, heat-reducing measures, water-saving strategies, and flood-protection technologies are recommended. With regard to urban planning, current science highlights the role of urban green, although recommendations on the specific structure, design and distribution still vary (cp. findings from Müller et al. (2014) and Doick et al. (2014) in the previous Chapter).

In order to evaluate the applicability of the main identified GHG reduction options,

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[40] In particular, heat management strategies were found to be missing (Stone et al., 2012).

[41] Affecting means for daytime and nighttime, as well as extreme temperatures.

presented in Part IV, the discussion should focus on whether an increasing HH size or a larger amount of compact inner-urban area (increasing ED of the LULC class DDUF) is compatible with an increasing amount of urban green. Additionally, consideration should be given to the higher GHG emissions resulting from urban sprawl, which relate to less dense urban fabrics such as those caused by extensive parks or forests.

Considering that the growing number of people per household does not directly conflict with urban planning initiatives to incorporate more green areas into the urban fabric, investigations should focus on creating more compact (and fewer low-density) urban areas. However, various potential conflicts may arise in this regard. On the one hand, DDUF is defined as the urban space with the highest residential living density[42], mostly in cities' central areas. Here, people are already coping with the greatest UHI effects, and will also be the most affected by rising urban temperatures. Therefore, CC adaptation measures to lower further heating (such as green spaces or water areas) are strongly needed in these inner-urban locations. On the other hand, research findings recommend, that cities should increase such compact urban areas (if possible, without extensively large natural sites) to reduce their GHG emissions (Parts III and IV).

A possible solution to this obvious dilemma is related to the second component of the identified "compact urban area": the spatial metric ED. It describes the design of the addressed urban patches and thus, the overall LULC composition of the DDUF. Considering that a high ED of the DDUF correlates to lower emissions, a very "fragmented" LULC patchwork of this inner-urban area is recommended. In such an urban landscape, high-density urban patches (although not 100% sealed as for example, the CUF) could be mixed with small-scale greening projects and parks (incl. trees and green buildings). This concept would take other GHG drivers into account that were shown to also influence urban GHG emissions[43] (Part III). It would also be similar to solutions that Doick et al. (2014) found to be most effective for reducing urban temperatures in London. Furthermore, natural areas could be located closer to residents, which would also directly affect human well-being (Krekel et al., 2015; Stadt Nürnberg, 2012) and reduce transport demands for fulfilling populations' needs for natural areas[44] (Part III). In addition, small urban green sites were found to be important for local empowerment and creativity, which can also inspire a broader transformation of green infrastructure at the city level (Lovell and Taylor, 2013).

Moreover, concepts like the "green belt movement" in the UK (Part IV) could deliver important insights into counteracting urban sprawl (Baur et al., 2015a). Thus, cities'

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[42] Whereas CUF represents the highest overall soil sealing, DDUF is defined as the LULC class with the highest residential density.

[43] For example, large-scale green areas, forests, and water bodies, as well as large amounts of very low density urban areas were found to correlate with increasing GHG emissions per capita.

[44] For example, for leisure and recreational activities.

further outward expansion could for example be limited by developing “green belts” around the urban areas. These areas could also be used to improve the overall urban air quality, producing cooler air for lowering urban temperatures during summer time, and also mitigating effects of extreme precipitation events (by providing additional attenuation storage volume).

In the end, the successful development of an integrated urban CC master plan requires the consideration of both GHG mitigation and adaptation measures (Viegas et al., 2013). Therefore, the multi-level involvement of all stakeholders is required (Masson et al., 2014), as well as profound scientific knowledge on the main drivers of both fields, which applies also to practitioners and municipal governments (Oberlack and Eisenack, 2014; Wernstedt and Carlet, 2014). Reviews of current climate action plans for German and EU cities reveal that adaptation measures to future CC impacts have not been adequately addressed. Cities should mind this gap when revising their urban planning strategies and could also include the findings from this research, which have been shown to have the potential to link CC mitigation and adaptation, to develop comprehensive future urban development plans. In this context, the combination with urban modeling (e.g., including scenarios of future demographic trends) can be helpful to test different urban planning strategies and their effects also on the city’s GHG emission context.

V-5 Conclusions and outlook

The importance of cities for managing climate change is widely recognized both by science as well as by businesses who push the development of approaches forward to transform present urban areas into more sustainable cities of the future (Kessler, 2014a; Powell, 2015).

However, more thorough knowledge is required on the main urban GHG emission influences. This also includes a possibility for cities to uniformly take stock of their most important emissions. Therefore, the overarching goal of this thesis was to develop an approach that enables cities to easily estimate their GHG emissions. In order to develop such an approach, research was conducted to answer the following main research questions:

1. Which socioeconomic and spatial urban characteristics have the strongest influence on cities' GHG emissions?
2. Is it possible to focus on only a few specific GHG influences to ease the estimation of urban GHG emissions?

By subsequently analyzing the GHG emissions of EU cities, in particular the knowledge about the influence of a city's spatial layout on its emissions was expanded and it was shown that a limited number of highly significant GHG influences is already sufficient for estimating urban GHG emissions in the EU. The results revealed that, if the socioeconomic variable "household size" and the spatial variable "edge density" of the LULC class "discontinuous dense urban fabric" (subsequently called "compact urban area") are jointly examined in a multiple linear regression model, it is possible to explain the vast majority of the investigated urban GHG emissions. Therefore, by developing a linear GHG emission model with only two main components, the second research question could be answered and an approach could be derived to help cities easily estimate and compare their GHG emissions. In particular, regarding the existing uncertainty in urban GHG emissions (s. Chapter I-2), this research can help advance the understanding of cities' role for CC mitigation.

While analyzing EU urban GHG emissions, previous assumptions about the influence of specific parameters were also re-investigated. Thus, the relation between population density and emissions was found to be less clear than initially expected. Instead, the identified "compact urban area" appears to be a more useful indicator of GHG emissions, even though it correlates with population density. An explanation is that the indicator "compact urban area" focuses particularly on the LULC class discontinuous dense urban fabric and thus supports a more intra-urban analysis of GHG emissions than would analyses of the overall urban population density. Also, linkages between income-related indicators and urban GHG emissions were found to be more complex than previously thought (e.g., for transport-related emissions) and only a weak correlation between personal wealth and overall EU urban GHG emissions could be identified. However, even this weak correlation was reduced after correcting for varying electricity CO_2 emissions. A main reason is that personal wealth, among other variables, describes population lifestyles. Thus, it mostly relates to indirect urban GHG emissions (caused by e.g., consumption habits). However, the analyzed emissions mostly cover direct emissions and are therefore less useful for showing the relevance of wealth for controlling urban GHG emissions (Chapter V-1). Additionally, climate variables (such as HDD or CDD) could not be tested due to data constraints (Chapter I-5.2.1).

Overall, this study highlights the importance for controlling urban sprawl by considering the relevance of household sizes and compact urban areas for limiting urban GHG emissions. Considering that the current EU urbanization trend can be characterized by urban sprawl patterns and decreasing household sizes (although not decreasing land consumptions), and acknowledging future CC related urban challenges (GHG reduction and adaptation to changing climatic conditions), addressing the identified urban GHG influences presents a timely issue for EU cities. The consideration of predicted future demographic changes[45] illustrates the particular relevance of household sizes for future urban development and energy consumption (Alders and Manting, 2001; Sinclair, 2004; Surkyn and Lesthaeghe, 2004).

In this context, the findings highlight potential risks[46], but also opportunities for implementing more sustainable urban developments. Thus, for example, the creation of incentives for sharing living space or supporting inter-generational and young families should be considered for increasing urban household sizes (Baur et al., 2015b). Mixing compact urban areas with small scale urban green spaces is also found to be a suitable urban planning approach to lower emissions per capita and also create a more climate-resilient urban landscape (i.e., to rising urban temperatures and heavy precipitation events). Furthermore, such urban areas are expected to boost long-term urban productivity, as they result not only in social and natural benefits, but also in a huge potential for reduced infrastructure investments of > US$ 3 trillion over the next 15 years (The New Climate Economy, 2014). Therefore, particularly concerning

[45] It is expected that family household sizes decrease and the numbers of smaller households increase in EU cities (Part IV).

[46] GHG emissions per capita may increase due to smaller household sizes or the urban population may become more vulnerable due to an increase of elderly households (Długosz, 2011).

future demographic developments with more CC-vulnerable urban inhabitants, these findings present important aspects that should be taken into account for future urban management (Powell, 2015).

In general, it was shown that the consideration of specific urban characteristics (e.g., population size, population growth, and geographical location) can support analyses of urban GHG emissions. In addition, it was also found that the specific types of electricity production can have a strong influence on urban GHG emissions. Thus, analyses of less obvious GHG drivers can be supported by considering "varying energy influences". As discussed, the introduced method to account for these variations represents a feasible approach for cities with similar electricity GHG intensities (Chapter V-4.2.2). However, when energy intensities strongly diverge from the (EU) averages, this approach might be too general and the developed model might under- or overestimate GHG emissions (e.g., for the French and Swedish cities). As shifts towards more renewable energies change the relevance for electricity in all sectors (Agora Energiewende, 2014), it also becomes more important in resident's daily lives. Also, due to the fact that energy-related CO_2 emissions are one of the most important global GHG emission drivers (Chapter I-5.2.1), varying electricity emissions require close attention when comparing international GHG data. Therefore, future research should develop a more thorough mechanism for handling the identified electricity influence.

Considering the complexity of a quantitative analysis of urban GHG emissions, the relevance of a comparable database was underlined. Therefore, focusing on EU cities helped to maintain high quality-data standards and enabled a thorough GHG analysis. The identification of uniformly assessable GHG influences (household sizes and edge density of discontinuous dense urban fabric) for modeling emissions presents a strong advantage of the introduced approach, particularly for cities with less CC competence. Nevertheless, it needs to be considered that the conclusions strongly depend on the analyzed data, which, particularly for the GHG data, represents a potential source of uncertainty (Chapter V-4.2.1).

Future research should elaborate on the presented findings. For example, GHG estimations could be performed for an additional 97 cities in the EU (using the data sources introduced in Chapter VI-3), which were not included in this research due to a lack of suitable GHG data. However, with the respective information available, the identified GHG influences could be evaluated and the introduced GHG estimation model refined, also in consideration of different city archetypes. Furthermore, an expansion beyond EU borders is expected to reveal valuable insights into the influence of regional specific characteristics on urban GHG emissions (and thus, into other potentially important variables). In particular, societally-influenced habits might be an important variable, since social customs and traditions also shape populations' everyday lives. Despite containing information from various EU countries, these differences might have been less detectable in this study than a multi-continental investigation might have revealed.

Therefore, future research should further test the developed methodologies and the presented GHG estimation model (incl. assumptions on the most important GHG influences) in different regional settings. In consideration of future urbanization trends, particularly cities in Asia and in Latin America should be analyzed, if data are available. US cities might also be investigated. However, as these cities were already analyzed by various studies (Chapter I-2), new insights into their climate influence might be limited.

With the spatial scale of the analysis also being a relevant factor for urban GHG analysis (Part II), assumptions should be re-investigated over different spatial scales and with varying sample sizes. Thus, more general assumptions from larger data samples might be specified for distinctive city types (Part II), or for single urban areas. Furthermore, including more emission sources, in particular for indirect (scope 3) emissions, can help to better include citizens' lifestyles and thus, more comprehensively analyze the overall emission pattern (required e.g., for international analyses that investigate income and trade-related drivers). In this context, the consideration of LUZs (if appropriate data are available) might be useful, for example, to further analyze transportation habits.

In the end, the identified insights into urban GHG emissions should be used by practitioners. Especially if cities already have a profound knowledge (and data) about their emission situation, the application of the presented research findings can strongly help to revise conclusions about their strongest GHG influences. Concurrently, the introduced model can be refined and adapted to cities' specific needs. Even if respective cities do not, for example, have precise information about their climate impact, or if they want to validate other calculations, the presented approach might be useful for learning about their climate impact[47]. Especially when combined with existing urban and demographic development scenarios, the revealed insights into urban GHG emissions can facilitate more accurate long-term urban planning and help to create more climate-friendly and resilient cities. The modeling results were able to illustrate the distinctive climate impacts of urban developments and thus, can help to establish a multi-level dialog on how to promote sustainable urban lifestyles (also anticipating behavioral changes). Research should actively support this process[48] by for example, initiating city-specific case studies with relevant urban areas. Due to its regional and international relevance, its strong urban dynamics and its good environmental data availability, a first candidate might be the city of Berlin. The existence of agent-based ecosystem and demographic models[49] forms a good foundation for including GHG emission implications into urban planning modeling.

[47] Not only the final GHG estimation model might help cities to learn about their biggest emission drivers, but also the other identified socioeconomic and spatial emission influences (in Part II-III).

[48] The *Nationale Plattform Zukunftsstadt* is a new initiative to ally research with cities, governments, and the private sector to create more climate-resilient urban areas (BMBF, 2015).

[49] For example, the Technische Universität Berlin (*Geoinformation in Environmental Planning Lab*) or the Humboldt Universität (*Department of Landscape Ecology*) perform such research.

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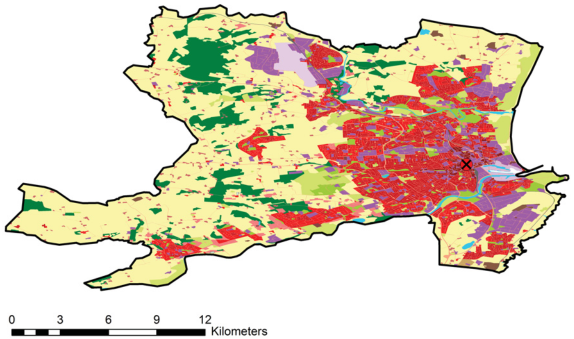
Part VI

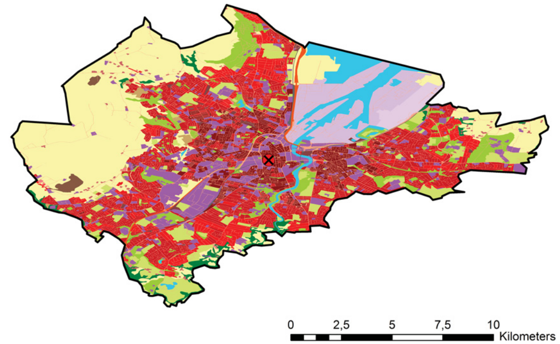
Appendix

VI-1 Urban Atlas data for all cities under spatial investigation

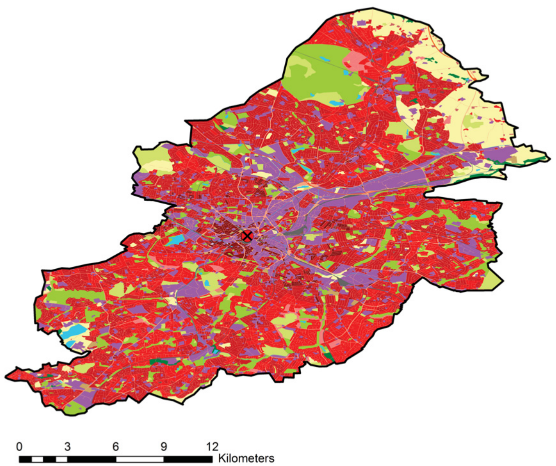
Table VI-1: Urban Atlas data for all 52 EU cities under spatial analysis (excluding cities shown in Figure I-4, sorted alphabetically, information about the specific LULC classes are presented in Chapter VI-2)



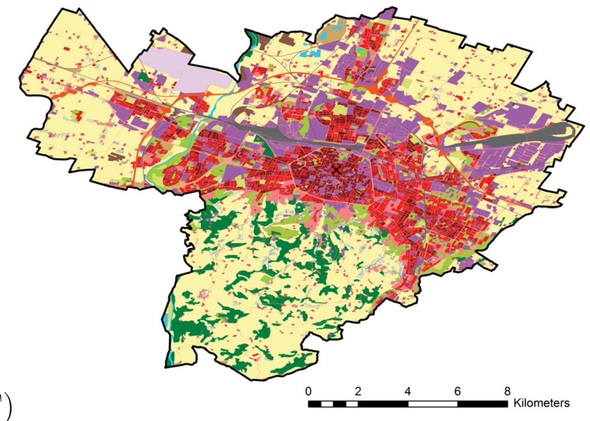
Aberdeen (UK)



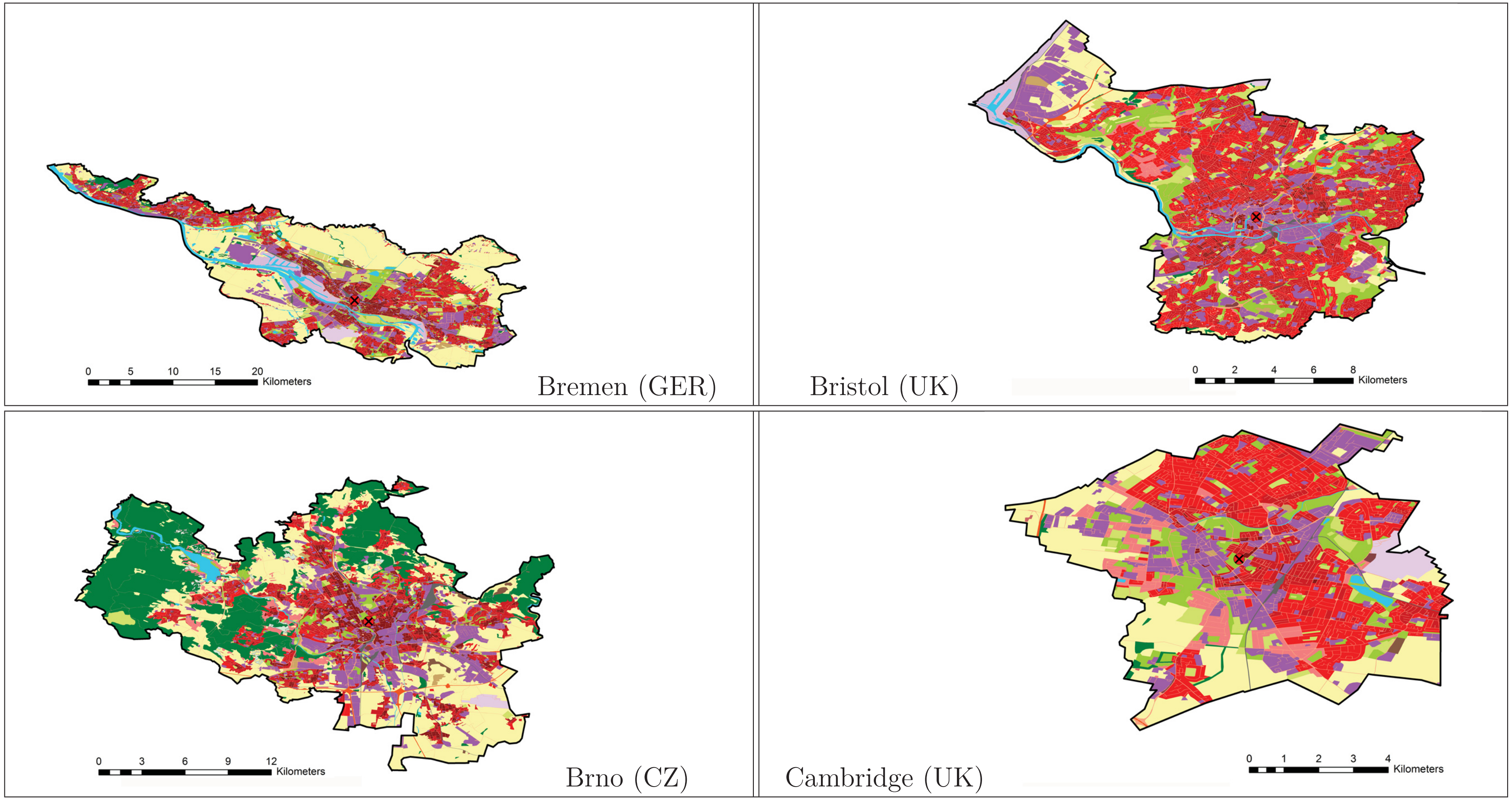
Belfast (UK)

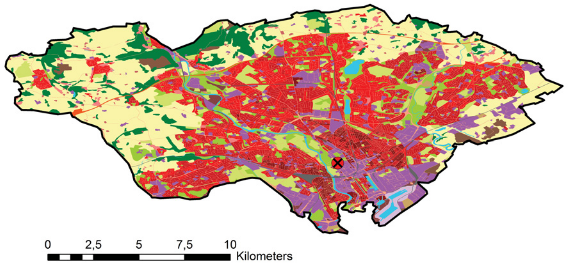


Birmingham (UK)

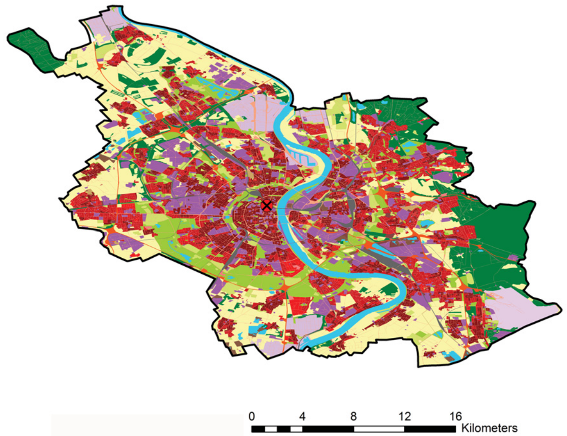


Bologna (IT)

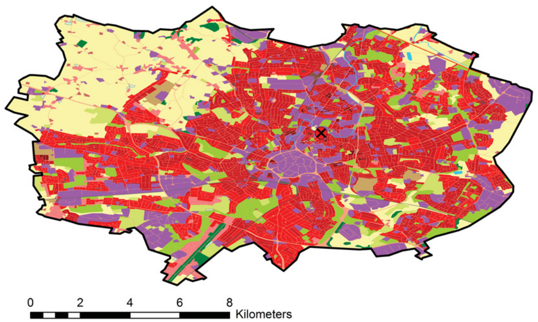

0 5 10 15 20 Kilometers
Bremen (GER)
Bristol (UK)
0 2 4 6 8 Kilometers
0 3 6 9 12 Kilometers
Brno (CZ)
Cambridge (UK)
0 1 2 3 4 Kilometers



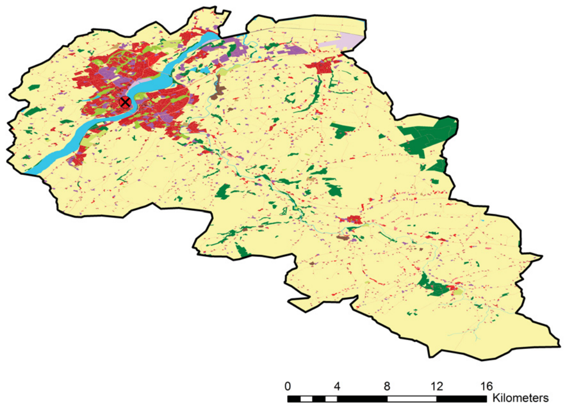
Cardiff (UK)



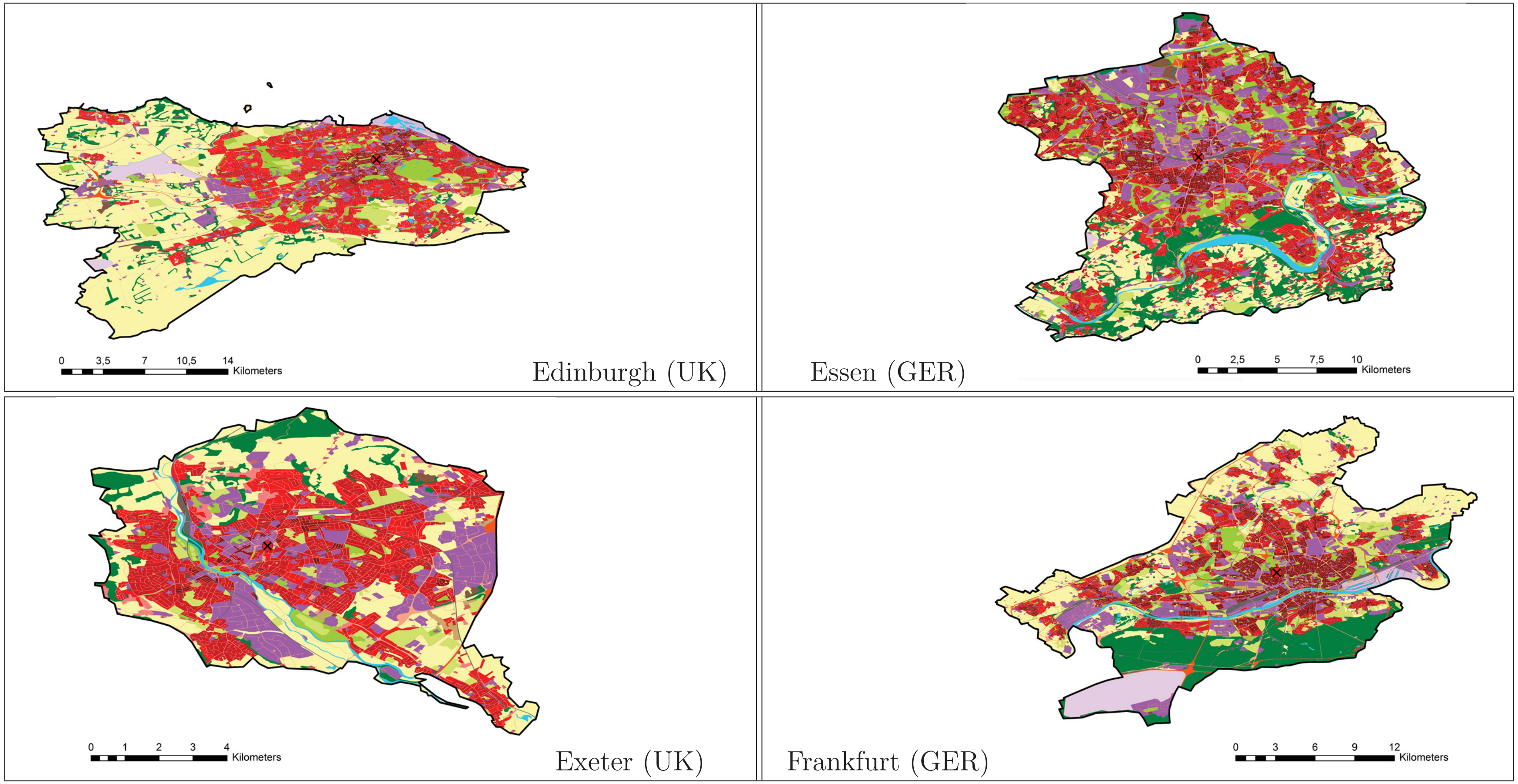
Cologne (GER)

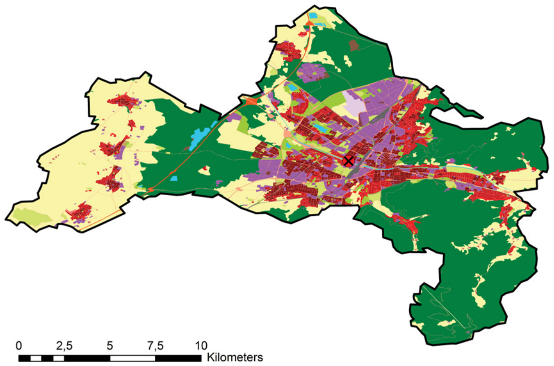


Coventry (UK)

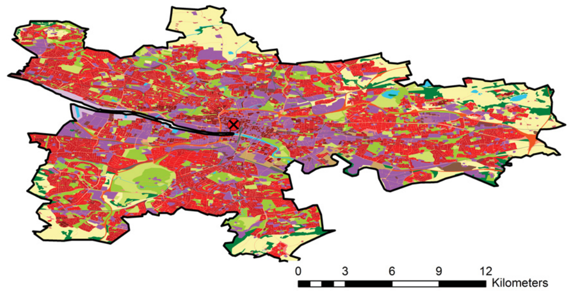


Derry (UK)

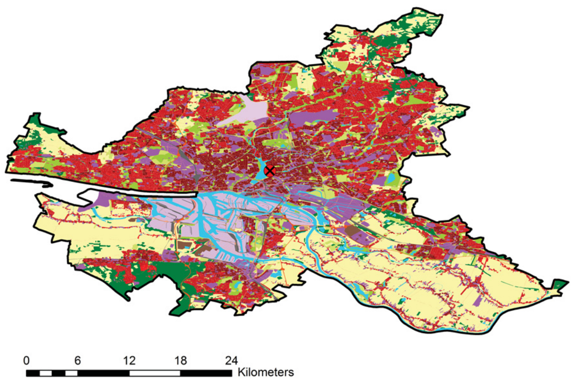

0 3,5 7 10,5 14 Kilometers
Edinburgh (UK)
Essen (GER)
0 2,5 5 7,5 10 Kilometers
0 1 2 3 4 Kilometers
Exeter (UK)
Frankfurt (GER)
0 3 6 9 12 Kilometers



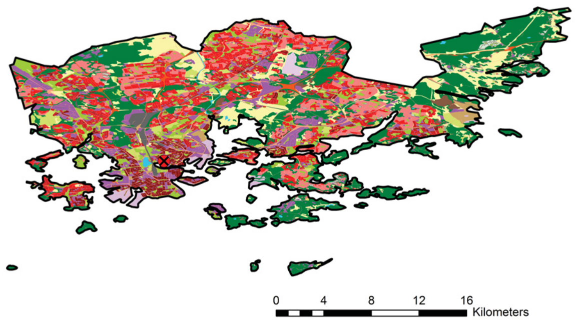
Freiburg (GER)



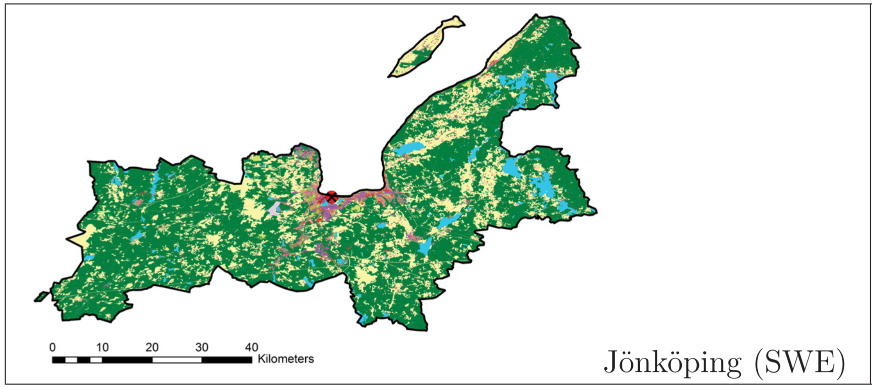
Glasgow (UK)

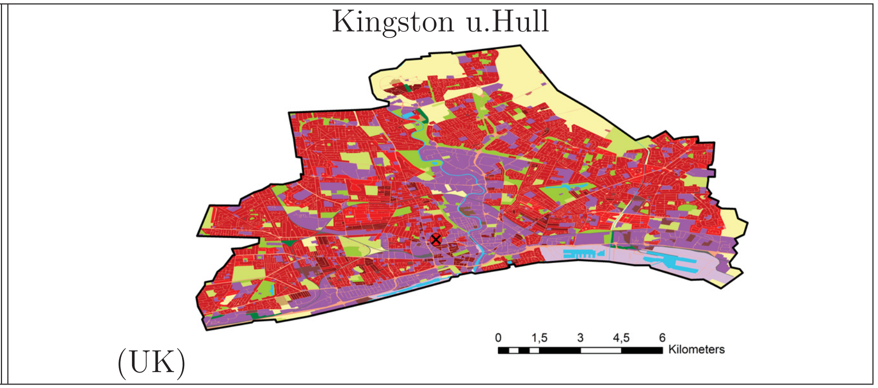


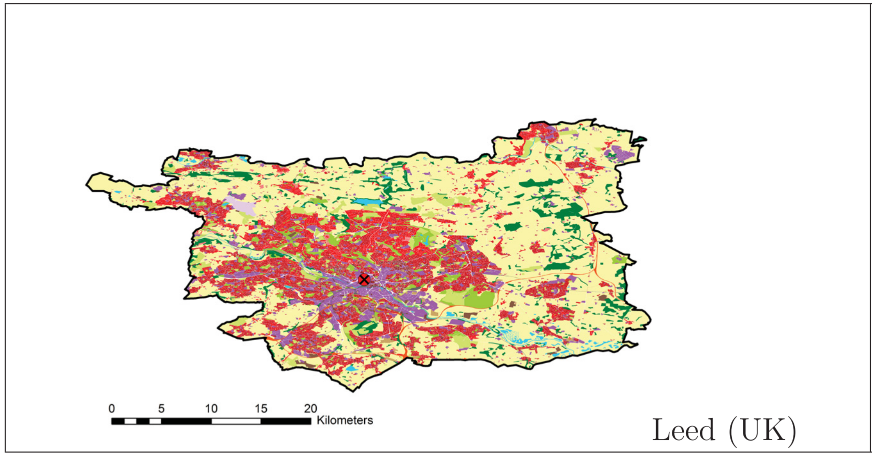
Hamburg (GER)

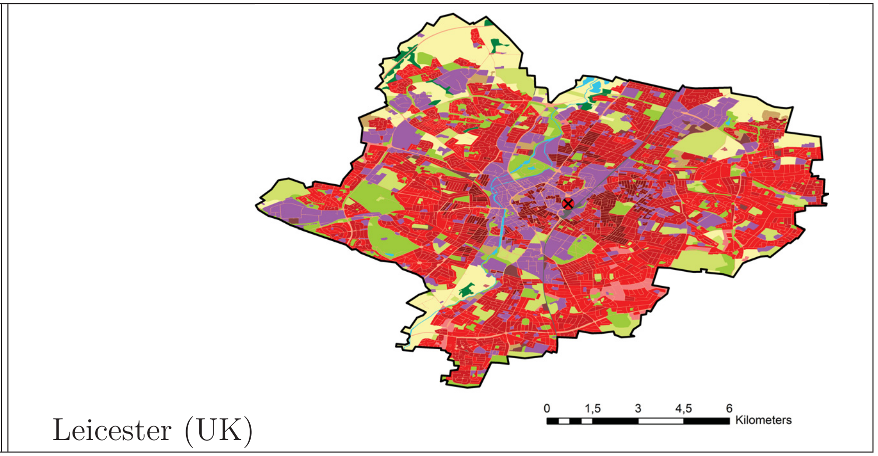


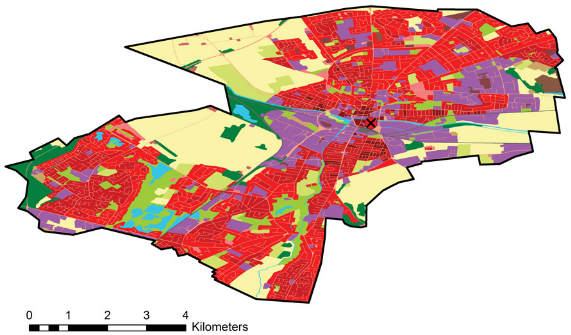
Helsinki (FI)


0 10 20 30 40
Kilometers
Jönköping (SWE)

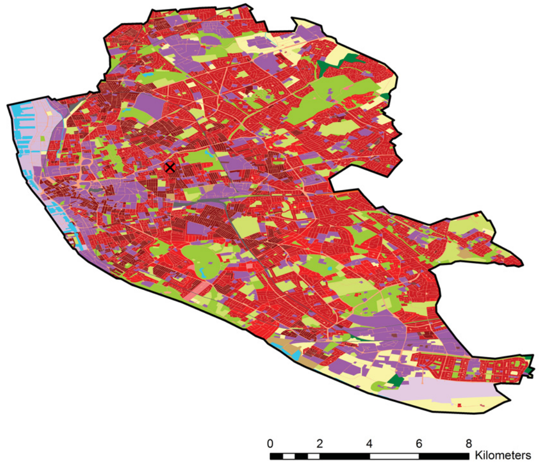

Kingston u.Hull
(UK)
0 1,5 3 4,5 6
Kilometers


0 5 10 15 20
Kilometers
Leed (UK)

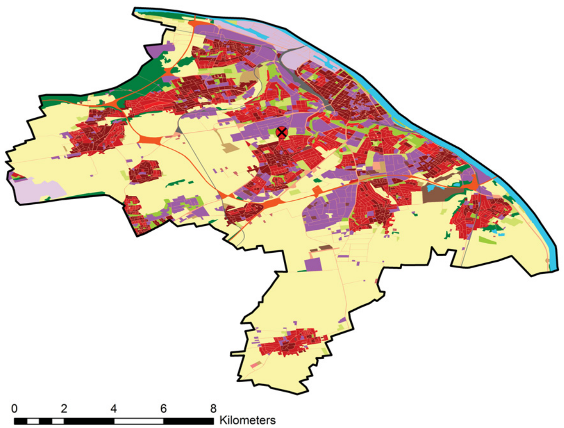

0 1,5 3 4,5 6
Kilometers
Leicester (UK)



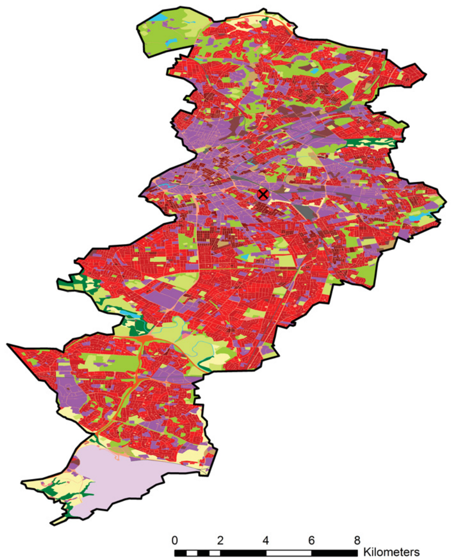
Lincoln (UK)



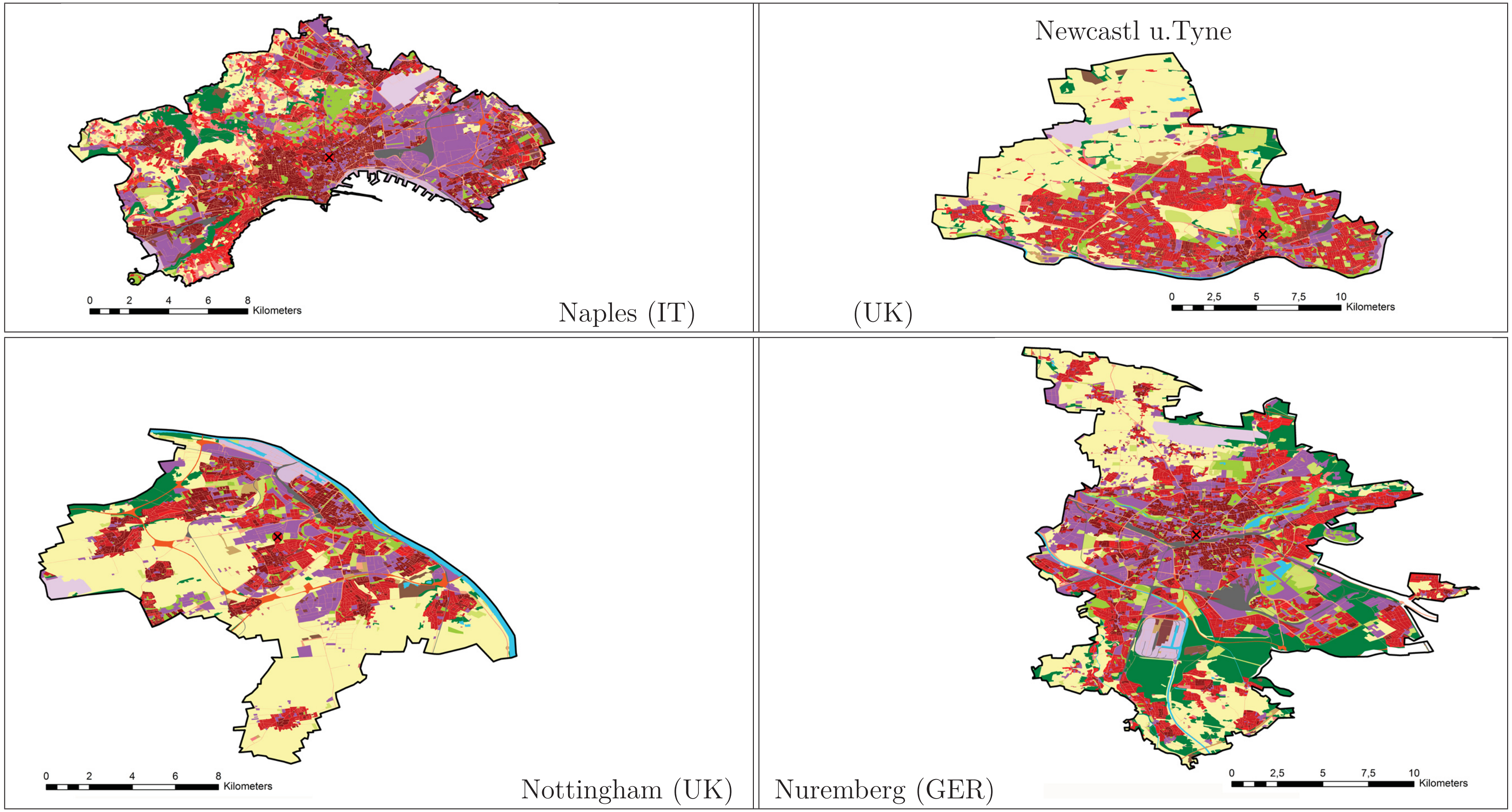
Liverpool (UK)

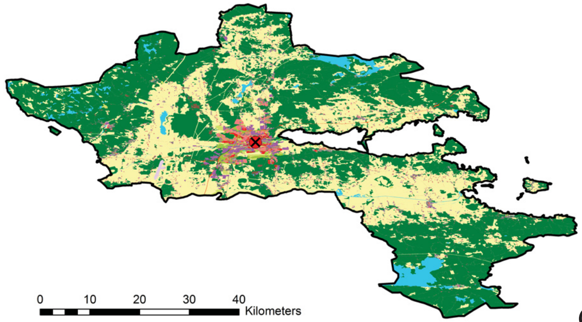


Mainz (GER)

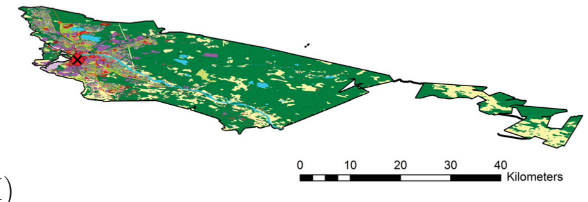


Manchester (UK)

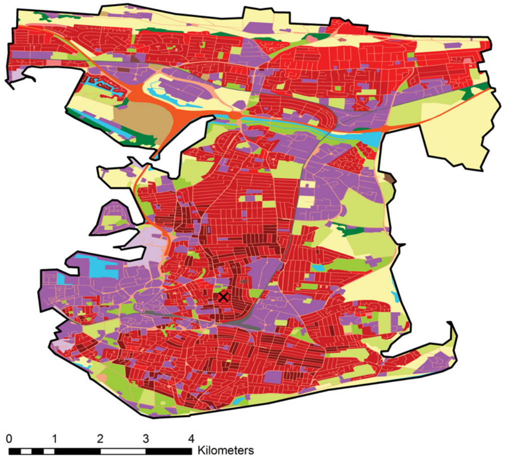

0 2 4 6 8 Kilometers
Naples (IT)
Newcastl u.Tyne
(UK)
0 2,5 5 7,5 10 Kilometers
0 2 4 6 8 Kilometers
Nottingham (UK)
Nuremberg (GER)
0 2,5 5 7,5 10 Kilometers



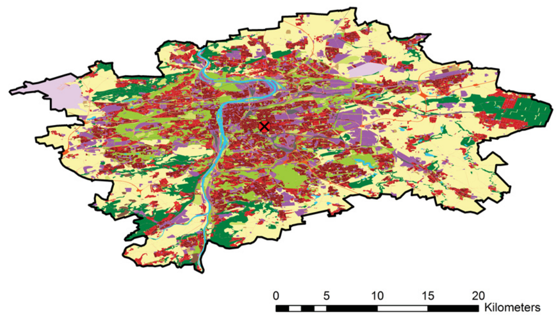
Örebro (SWE)



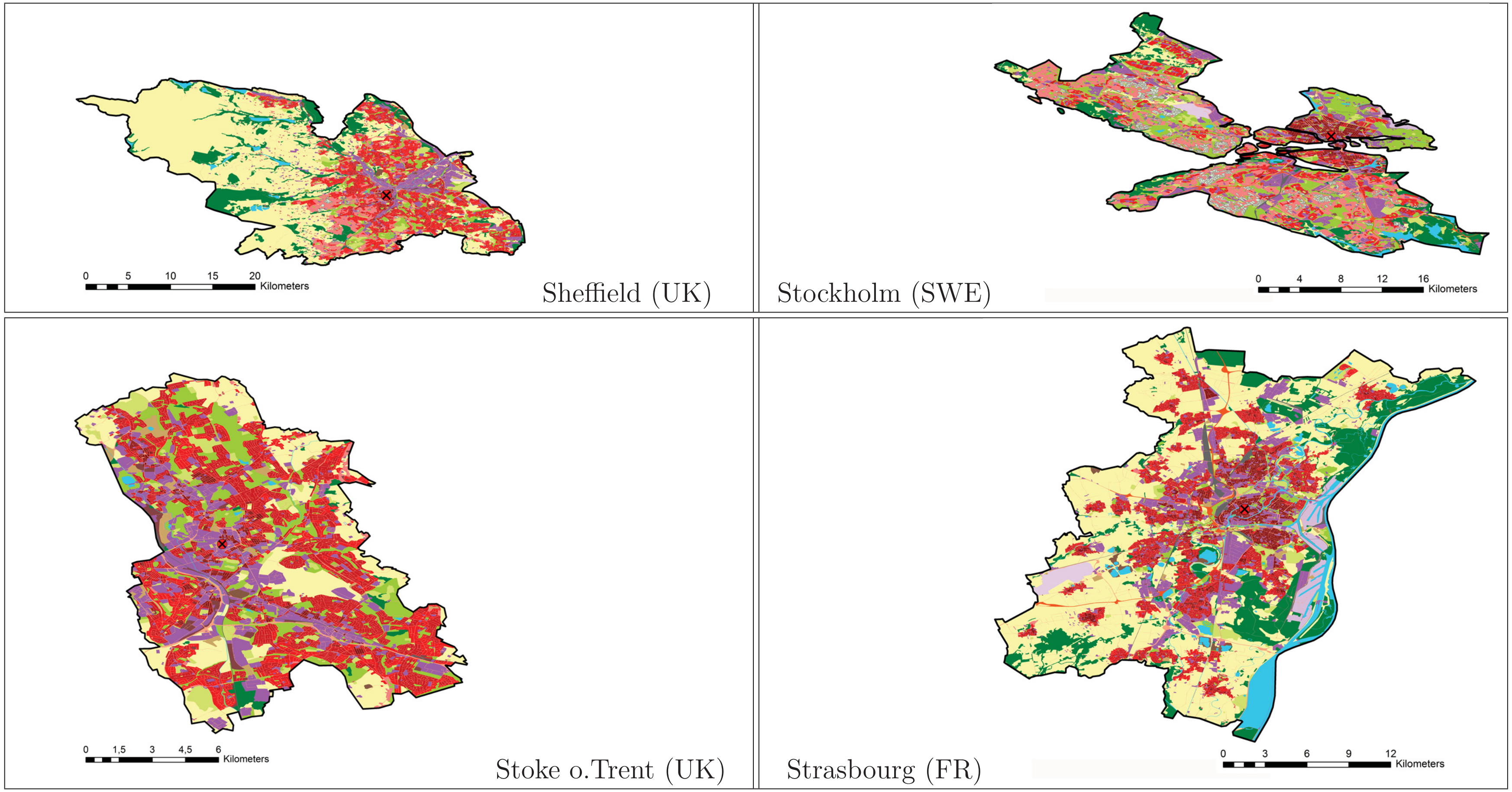
Oulu (FI)

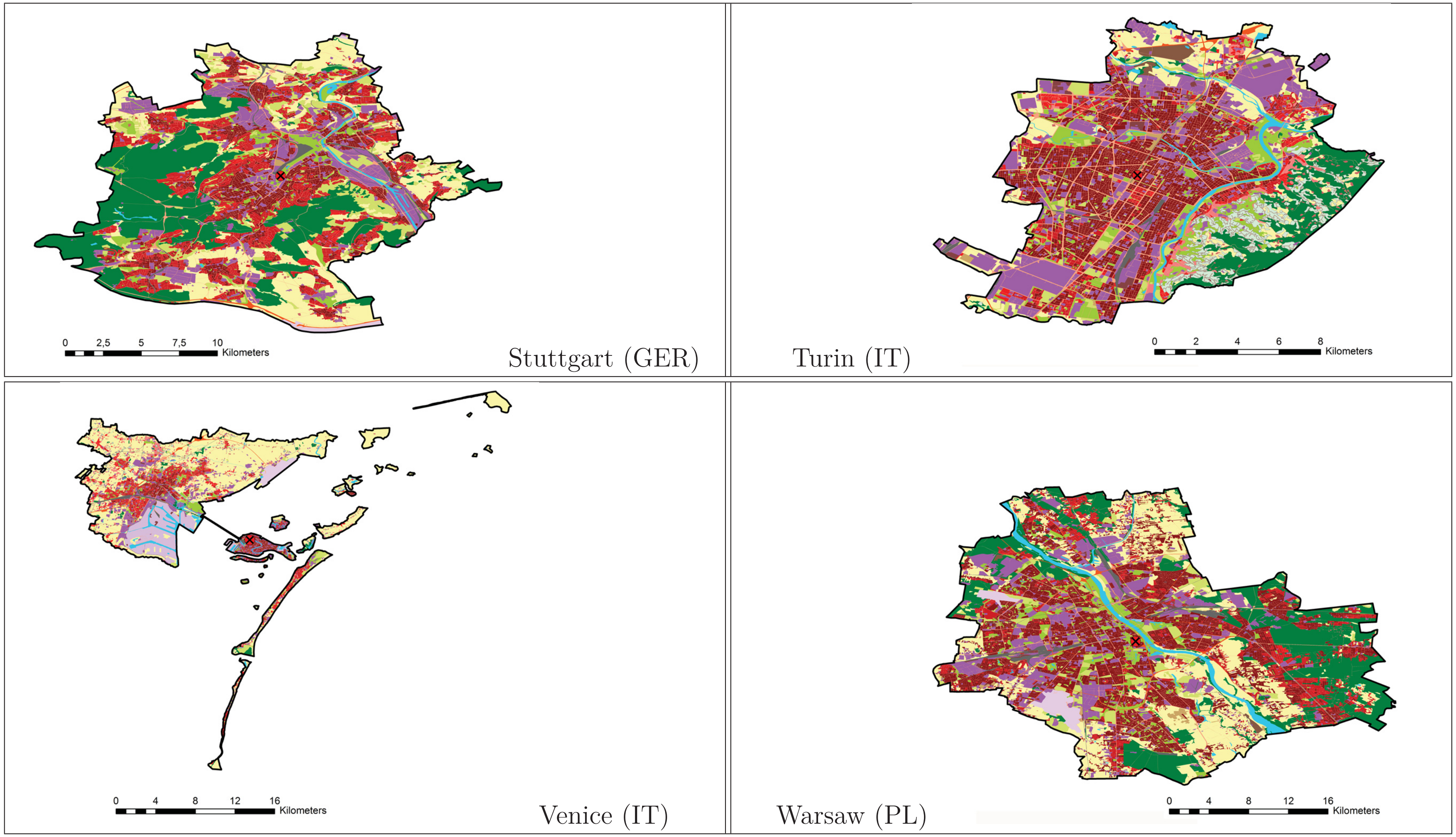


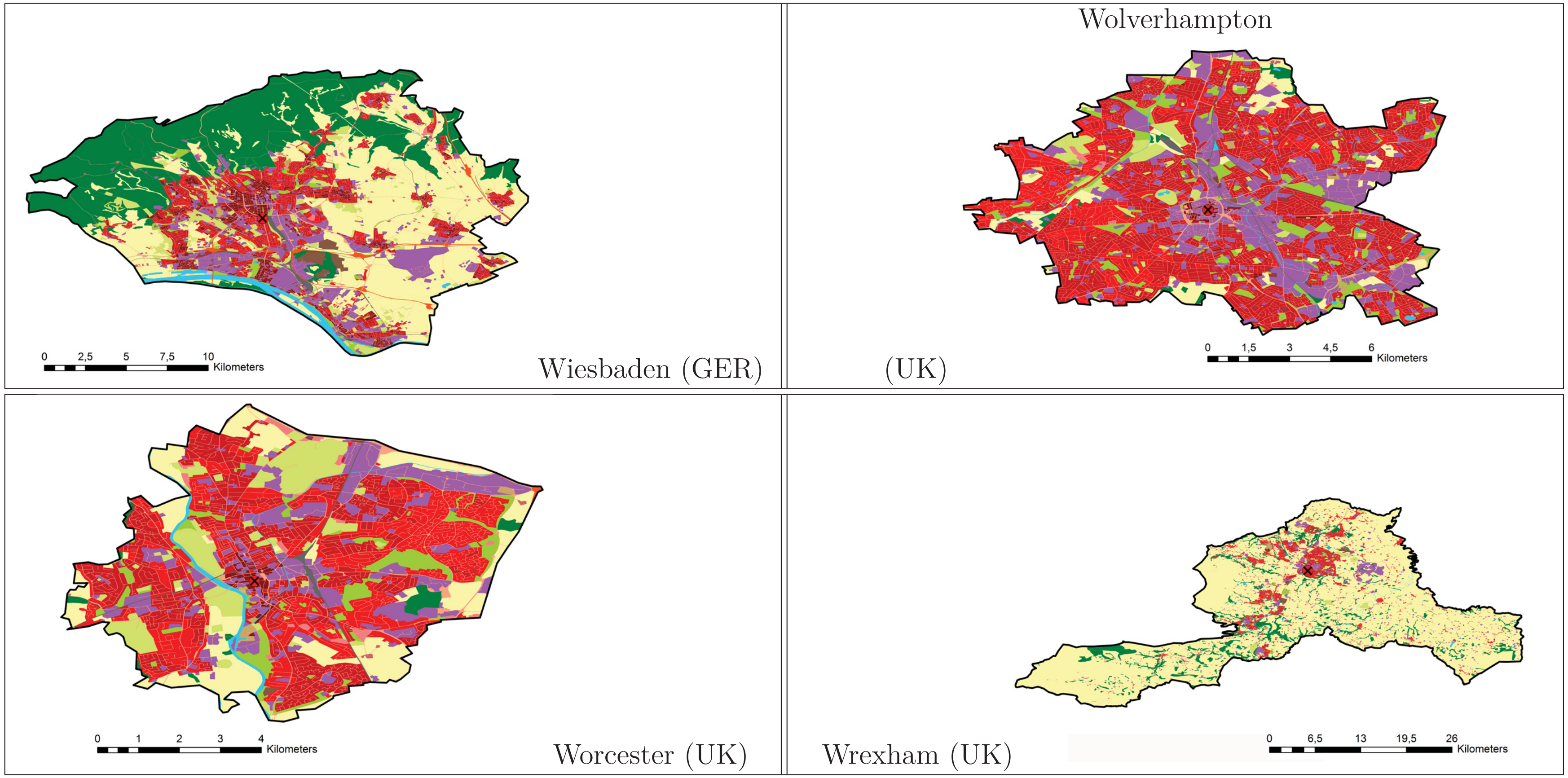
Portsmouth (UK)



Prague (CZ)


0 5 10 15 20 Kilometers
Sheffield (UK)
Stockholm (SWE)
0 4 8 12 16 Kilometers
0 1,5 3 4,5 6 Kilometers
Stoke o.Trent (UK)
Strasbourg (FR)
0 3 6 9 12 Kilometers


0 2,5 5 7,5 10
Kilometers
Stuttgart (GER)
Turin (IT)
0 2 4 6 8
Kilometers
0 4 8 12 16
Kilometers
Venice (IT)
Warsaw (PL)
0 4 8 12 16
Kilometers



0 2,5 5 7,5 10 Kilometers
Wiesbaden (GER)
Wolverhampton
(UK)
0 1,5 3 4,5 6 Kilometers
0 1 2 3 4 Kilometers
Worcester (UK)
Wrexham (UK)
0 6,5 13 19,5 26 Kilometers

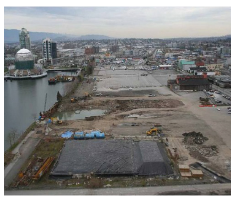
VI-2 All Urban Atlas LULC classes under spatial analysis

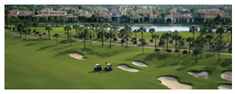
Table VI-1: All Urban Atlas LULC classes under spatial analysis

#	UA color coding	LULC class	Short description[50]	Illustration
1		Continuous Urban Fabric	Average degree of soil sealing: > 80% Example: Areas covered with buildings, roads and sealed areas. Unplanned areas of vegetation and bare soil are exceptional.	
2		Discontinuous Dense Urban Fabric	Average degree of soil sealing: > 50 - 80% Examples: Residential buildings, roads and other artificially surfaced areas.	
3		Discontinuous Medium Density Urban Fabric	Average degree of soil sealing: > 30 - 50% Example: Residential buildings, roads and other artificially surfaced areas. However, vegetated areas are predominant (although the land is not dedicated to forestry or agriculture).	
4		Discontinuous Low Density Urban Fabric	Average degree of soil sealing: > 10 - 30% *Usage is comparable to DMDUF but less dense.*	

[50] Further information can be found in European Environment Agency and Meirich (2011)

5		Discontinuous Very Low Density Urban Fabric	Average degree of soil sealing: <10 % Residential buildings, roads and other artificially surfaced areas. The vegetated areas are predominant, but the land is not dedicated to forestry or agriculture. Example: exclusive residential areas with large gardens.	
6		Isolated structures	Isolated artificial structures (with residential component), not surrounded by any urban class or transportation network Example: individual farm houses	
7		Industrial, commercial, public, military and private units	Average degree of soil sealing: >30 % More than 50% of artificial surface is occupied by buildings/- structures with non-residential use (industrial, commercial or transport related uses are dominant)Examples: Schools, hospitals, production sites, shopping centers office-buildings.	
8		Fast transit roads and associated land	Examples: motorways/ highways incl. parking, rest and service areas.	
9		Other roads and associated land	Roads, crossings, intersections and parking areas, including roundabouts and sealed areas with “road surface”.	
10		Railways and associated land	Railway facilities including stations, cargo stations and service areas.	

11		Port areas	Administrative area of ports. Examples: inland harbours and sea ports, infrastructure of port areas, including quays, dockyards, transport and storage areas and associated areas (not included: marinas).	
12		Airports	Administrative area of airports, mostly fenced. Examples: all airport installations: runways, buildings and associated land (not included: aerodromes without sealed runaway).	
13		Mineral extraction and dump sites	• Open pit extraction sites (sand, quarries) including water surface, if < MinMU, open-cast mines, inland salinas, oil and gas fields • Their protecting dikes and / or vegetation belts and associated land such as service areas, storage depots • Public, industrial or mine dump sites, raw or liquid wastes, legal or illegal, their protecting dikes and / or vegetation belts and associated land such as service areas.	
14		Construction sites	Spaces under construction or development (e.g., with soil or bedrock excavations for construction purposes or other earthworks visible).	
15		Land without current use	Areas in the vicinity of artificial surfaces still waiting to be used or re-used. Areas are obviously "in transitional to be used". Examples: Waste land, "brown fields", or "green fields" (not included: areas for actual agricultural or recreational use).	

16		Green urban areas	• Public green areas for predominantly recreational use and suburban natural areas that have become and are managed as urban parks. • Forests or green areas extending from the surroundings into urban areas included when at least two sides are bordered by urban areas and structures, and traces of recreational use are visible. Examples: zoos, parks, castle parks (not included: Private gardens, cemeteries, “unmanaged urban green areas”).	
17		Sports and leisure facilities	Public areas that are managed for sports and leisure uses. Examples: Sport fields, golf courses. Riding grounds, leisure parks, “Theresienwiese” in Munich.	
18		Agricultural areas, semi-natural areas and wetlands	Examples: Arable lands (fields under rotation system), permanent crops (vineyards), pasture and natural grasslands.	
19		Forests	All water bodies and water courses are considered as long as they exceed an area of 1ha. Including • Sea, lakes, reservoirs, canals Fish ponds (natural, artificial) (ponds with distance $<$ 10 m	
20		Water	All water bodies and water courses are considered as long as they exceed an area of 1ha. Including • Sea, lakes, reservoirs, canals • Fish ponds (natural, artificial) (ponds with distance $<$ 10 m	

Sources of illustrations:

1. http://www.google.de/imgres?imgurl=http%3A%2F%2Fwww.patrikschumacher.com%2FImages%2FDigital%252520Cities%2FZHA__Istanbul__cross-towers__sm.jpg&imgrefurl=http%3A%2F%2Fwww.patrikschumacher.com%2FTexts%2FParametricism%2520-%2520A%2520New%2520Global%2520Style%2520for%2520Architecture%2520and%25Urban%2520Design.html&h=722&w=962&tbnid=Z-IKCPHMWJbFsM%3A&zoom=1&docid=18oPdDP9JpPM0M&ei=-nrTVMj8DMP0UvWUg4AE&tbm=isch&iact=rc&uact=3&dur=87&page=1&start=0&ndsp=41&ved=0CCIQrQMwAA
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VI-3 Further potential EU cities for estimating urban GHG emissions

As mentioned in Chapter V-5, considering the importance of the household size and the edge density of the discontinuous dense urban fabric for estimating urban GHG emissions in EU, the introduced data sources allow the investigation of 97 further EU cities. The following map and list provide more precise information.

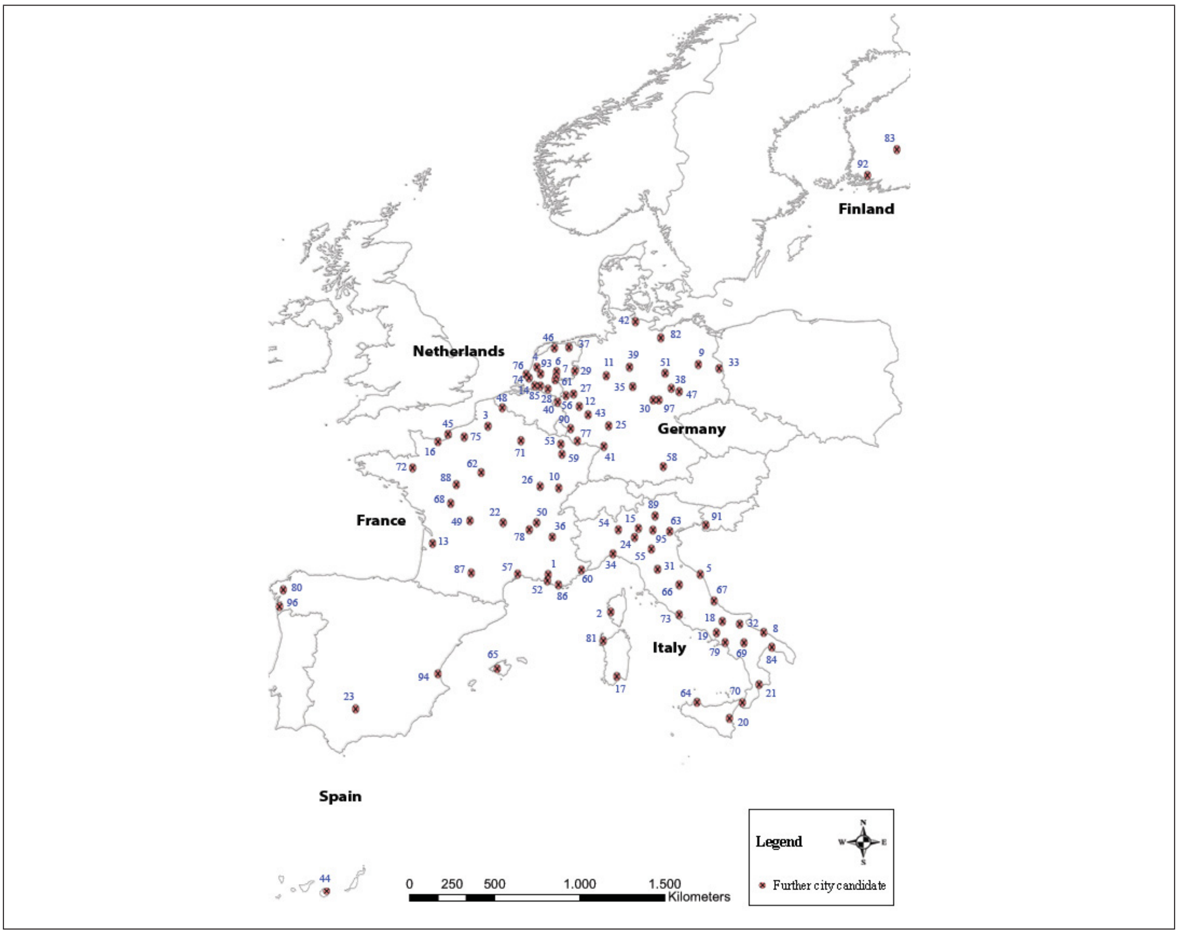

Figure VI-1: 97 further potential cities for estimating urban GHG in EU

#	City	Country	#	City	Country
1	Aix-en-Provence	FR	**41**	Karlsruhe	DE
2	Ajaccio	FR	**42**	Kiel	DE
3	Amiens	FR	**43**	Koblenz	DE
4	Amsterdam	NL	**44**	Las Palmas	ES
5	Ancona	IT	**45**	Le Havre	FR
6	Apeldoorn	NL	**46**	Leeuwarden	NL
7	Arnhem	NL	**47**	Leipzig	DE
8	Bari	IT	**48**	Lille	FR
9	Berlin	DE	**49**	Limoges	FR
10	Besançon	FR	**50**	Lyon	FR
11	Bielefeld	DE	**51**	Magdeburg	DE
12	Bonn	DE	**52**	Marseille	FR
13	Bordeaux	FR	**53**	Metz	FR
14	Breda	NL	**54**	Milano	IT
15	Brescia	IT	**55**	Modena	IT
16	Caen	FR	**56**	Mönchengladbach	DE
17	Cagliari	IT	**57**	Montpellier	FR
18	Campobasso	IT	**58**	München	DE
19	Caserta	IT	**59**	Nancy	FR
20	Catania	IT	**60**	Nice	FR
21	Catanzaro	IT	**61**	Nijmegen	NL
22	Clermont-Ferrand	FR	**62**	Orléans	FR
23	Córdoba	ES	**63**	Padova	IT
24	Cremona	IT	**64**	Palermo	IT
25	Darmstadt	DE	**65**	Palma de Mallorca	ES
26	Dijon	FR	**66**	Perugia	IT
27	Düsseldorf	DE	**67**	Pescara	IT
28	Eindhoven	NL	**68**	Poitiers	FR
29	Enschede	NL	**69**	Potenza	IT
30	Erfurt	DE	**70**	Reggio di Calabria	IT
31	Firenze	IT	**71**	Reims	FR
32	Foggia	IT	**72**	Rennes	FR
33	Frankfurt (Oder)	DE	**73**	Roma	IT
34	Genova	IT	**74**	Rotterdam	NL
35	Göttingen	DE	**75**	Rouen	FR
36	Grenoble	FR	**76**	s' Gravenhage	NL
37	Groningen	NL	**77**	Saarbrucken	DE
38	Halle an der Saale	DE	**78**	Saint-Etienne	FR
39	Hannover	DE	**79**	Salerno	IT
40	Heerlen	NL	**80**	Santiago de Compostela	ES

81	Sassari	IT	**90**	Trier	DE
82	Schwerin	DE	**91**	Trieste	IT
83	Tampere	FI	**92**	Turku	FI
84	Taranto	IT	**93**	Utrecht	NL
85	Tilburg	NL	**94**	Valencia	ES
86	Toulon	FR	**95**	Verona	IT
87	Toulouse	FR	**96**	Vigo	ES
88	Tours	FR	**97**	Weimar	DE
89	Trento	IT			