Landscape Ecol
DOI 10.1007/s10980-015-0169-5

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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Received: 14 February 2014 / Accepted: 7 February 2015

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

Electronic supplementary material The online version of this article (doi:10.1007/s10980-015-0169-5) contains supplementary material, which is available to authorized users.

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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),

Published online: 17 February 2015

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	Each LULC class
		It is calculated from NumP and the entire urban area	
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)

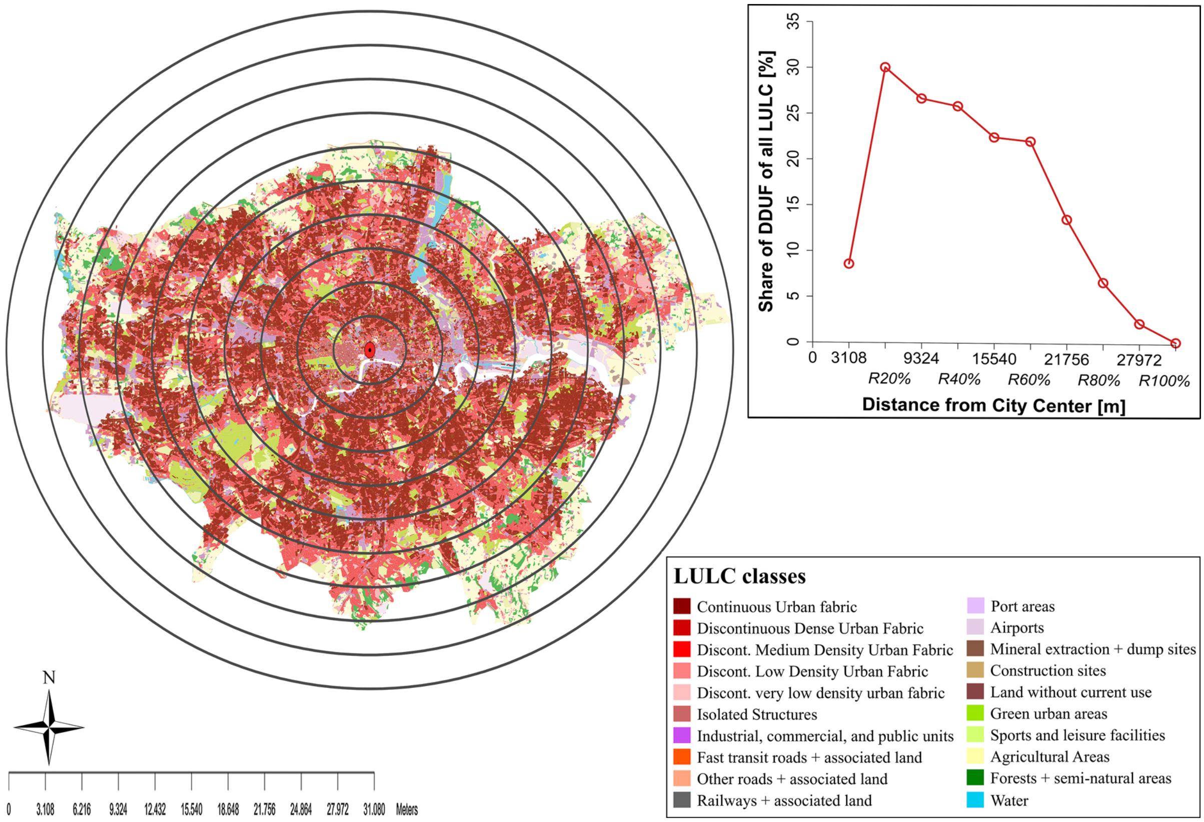

Fig. 1 Calculation of the LULC-based indicators. Using spatial data from European Union's "Urban Atlas", Fig. 1 presents the analysis of the LULC class *discontinuous dense urban fabric* in the city of London. The spatial distribution of the LULC class can be observed from darker patches in the spatial 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

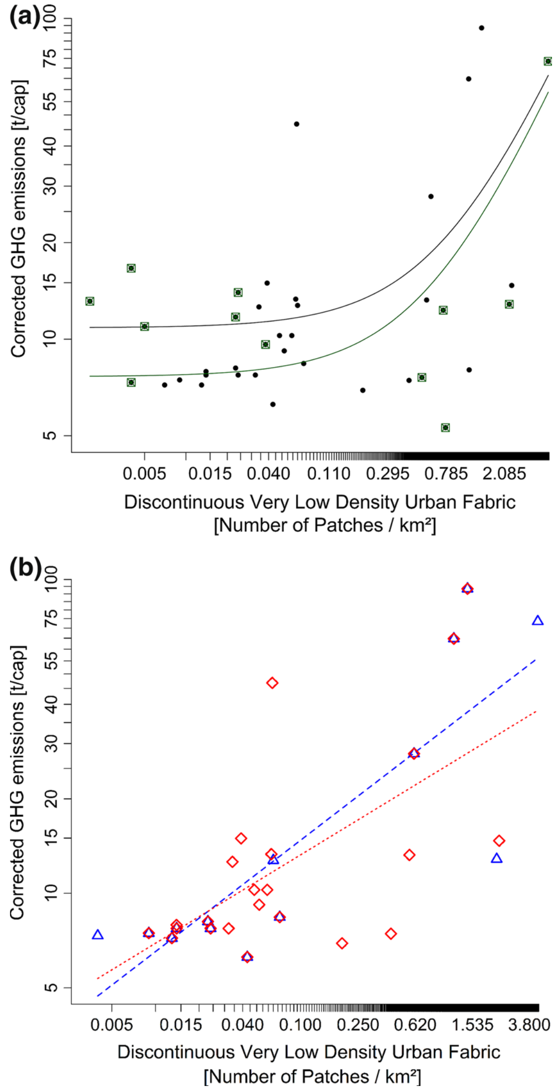

Fig. 2 Urban structure indicator *number of patches/km*^{2} of the LULC class *discontinuous very low density urban fabric*. **a** Linear correlations with urban GHG emissions per capita (*corrected for varying national energy mixes*) are shown for all EU cities (*black dots* and *black solid linear 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

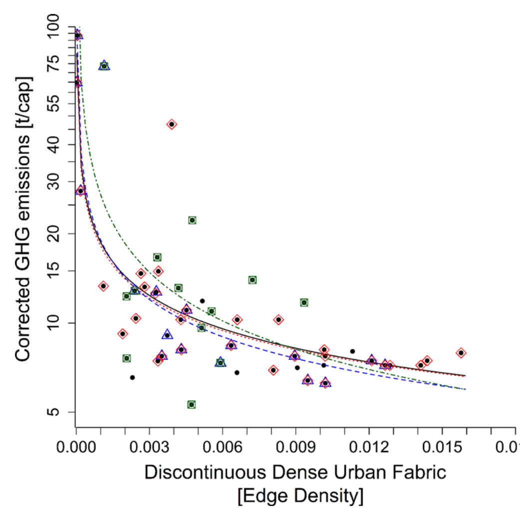

Fig. 3 Correlation between the urban structure indicator *edge density* of the LULC class *discontinuous dense urban fabric* and urban GHG emissions per capita (*corrected for varying national energy mixes*) are shown for all EU cities (*black dots* and *black solid linear fit-line*, $R^2 = 0.57$), medium-sized 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.

References

Ala-Mantila S, Heinonen J, Junnila S (2014) Relationship between urbanization, direct and indirect greenhouse gas emissions, and expenditures: a multivariate analysis. Ecol Econ 104:129–139. doi:10.1016/j.ecolecon.2014.04.019

Antrop M (2004) Landscape change and the urbanization process in Europe. Landsc Urban Plan 67:9–26

Baur AH, Thess M, Kleinschmit B, Creutzig F (2013) Urban climate change mitigation in Europe: looking at and beyond the role of population density. J Urban Plan Dev. doi:10.1061/(ASCE)UP.1943-5444.0000165

Bergeron O, Strachan IB (2011) CO2 sources and sinks in urban and suburban areas of a northern mid-latitude city. Atmos Environ 45:1564–1573. doi:10.1016/j.atmosenv.2010.12.043

Bhatia P, Ranganathan J (2004) The greenhouse gas protocol: a corporate accounting and reporting standard. WRI; WBSCD, Washington

CAPCOA (2010) Quantifying greenhouse gas mitigation measures

C40 Cities (2012) Global climate community releases city-scale emissions accounting standard for public comment. In: C40 Blog. http://www.c40.org/blog_posts/global-climate-community-releases-city-scale-emissions-accounting-standard-for-public-comment. Accessed 27 Sep 2014

Coutts A, Beringer J, Tapper N (2010) Changing urban climate and CO2 emissions: implications for the development of policies for sustainable cities. Urban Policy Res 28:27–47. doi:10.1080/08111140903437716

Creutzig F, Mühlhoff R, Römer J (2012) Decarbonizing urban transport in European cities: four cases show possibly high co-benefits. Environ Res Lett 7:044042. doi:10.1088/1748-9326/7/4/044042

Deng F, Huang Y (2004) Uneven land reform and urban sprawl in China: the case of Beijing. Prog Plan 61:211–236. doi:10.1016/j.progress.2003.10.004

Druckman A, Jackson T (2009) The carbon footprint of UK households 1990–2004: a socio-economically disaggregated, quasi-multi-regional input–output model. Ecol Econ 68:2066–2077. doi:10.1016/j.ecolecon.2009.01.013

ECOSPEED AG (2012) ECORegion—Die Lösung für effiziente Energie- und Treibhausgasbilanzierung für Städte und Gemeinden. In: ECOSPEED—Softw. Für Klimaschutz. http://www.ecospeed.ch/de/psc3_cenr20.html. Accessed 4 Jul 2012

El Nasser H, Overberg P (2001) A comprehensive look at sprawl in America. http://usatoday30.usatoday.com/news/sprawl/main.htm. Accessed 31 Jan 2014

ESRI (2012) ArcGIS for desktop 10.1. Environmental Systems Resource Institute (ESRI), Redlands

European Commission (2007) State of European cities report: adding value to the European

European Commission, Goulet R (2011) A European urban atlas: mapping land use in the 27 capital cities. Publications Office of the European Union, Luxembourg

European Environment Agency (1995) CORINE land cover. http://www.eea.europa.eu/publications/COR0-landcover. Accessed 29 Nov 2013

European Environment Agency (2006) Urban sprawl in Europe—the ignored challenge. Denmark, Copenhagen

European Environment Agency (2010) Urban environment—SOER 2010 thematic assessment

European Environment Agency (2012) Urban adaptation to climate change

European Environment Agency, Meirich S (2011) Mapping guide for a European Urban Atlas. http://www.eea.europa.eu/data-and-maps/data/urban-atlas/mapping-guide. Accessed 14 Nov 2013

Eurostat (2011) Data explorer. http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database. Accessed 20 Jul 2012

Ewing RH, Bartholomew K, Winkelman S, Walters J, Chen D (2007) Growing cooler: the evidence on urban development and climate change. Urban Land Institut, Washington

Feng L, Li H (2012) Spatial pattern analysis of urban sprawl: case study of Jiangning, Nanjing, China. J Urban Plan Dev 138:263–269. doi:10.1061/(ASCE)UP.1943-5444.0000119

Guariguata MR, Cornelius JP, Locatelli B, Forner C, Sánchez-Azofeifa GA (2008) Mitigation needs adaptation: tropical forestry and climate change. Mitig Adapt Strateg Glob Change 13:793–808. doi:10.1007/s11027-007-9141-2

Halsnæs K, Verhagen J (2007) Development based climate change adaptation and mitigation—conceptual issues and lessons learned in studies in developing countries. Mitig Adapt Strateg Glob Change 12:665–684. doi:10.1007/s11027-007-9093-6

Hartshorn TA (1992) Interpreting the city: an urban geography. Wiley, London

Heinonen J, Kyrö R, Junnila S (2011) Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki. Environ Res Lett 6:034034. doi:10.1088/1748-9326/6/3/034034

Herold M, Hemphill J, Dietzel C, Clarke KC (2005) Remote sensing derived mapping to support urban growth theory. In: 3rd International symposium on remote sensing. Data fusion urban areas URBAN 2005 5th International symposium on remote sensing of urban areas (URS 2005)

Hoornweg D, Sugar L, Trejos Gomez CL (2011) Cities and greenhouse gas emissions: moving forward. Environ Urban 23:207–227. doi:10.1177/0956247810392270

Huang J, Lu X, Sellers J (2007) A global comparative analysis of urban form: applying spatial metrics and remote sensing. Landsc Urban Plan 82:184–197. doi:10.1016/j.landurbplan.2007.02.010

IPCC (2014) Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, Mastrandrea PR, White LL (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1–32

Jackson T, Papathanasopoulou E (2008) Luxury or "lock-in"? An exploration of unsustainable consumption in the UK: 1968 to 2000. Ecol Econ 68:80–95. doi:10.1016/j.ecolecon.2008.01.026

Jenerette GD, Harlan SL, Brazel A, Jones N, Larsen L, Stefanov WL (2007) Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. Landscape Ecol 22:353–365. doi:10.1007/s10980-006-9032-z

Kennedy C, Steinberger J, Gasson B, Hansen Y, Hillman T, Havranek M, Pataki D, Phdungsilp A, Ramaswami A, Mendez GV (2009) Greenhouse gas emissions from global cities. Environ Sci Technol 43:7297–7302. doi:10.1021/es900213p

Kumar P (2010) The economics of ecosystems and biodiversity: ecological and economic foundations. UNEP/Earthprint, London

Lauf S, Hasse D, Kleinschmit B (2014) Linkages between ecosystem services provisioning, urban growth and shrinkage—a modeling approach assessing ecosystem service trade-offs. Ecol, Indic

Liao C-H, Chang C-L, Su C-Y, Chiueh P-T (2013) Correlation between land-use change and greenhouse gas emissions in urban areas. Int J Environ Sci Technol 10:1275–1286. doi:10.1007/s13762-012-0155-2

Lovell ST, Taylor JR (2013) Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landscape Ecol 28:1447–1463. doi:10.1007/s10980-013-9912-y

Maciag M (2014) Cities consider taxing commuters to drive up revenue. http://www.governing.com/news/headlines/gov-more-cities-could-tax-nonresident-workers-reverse-commuters.html. Accessed 22 Oct 2014

Makido Y, Dhakal S, Yamagata Y (2012) Relationship between urban form and CO2 emissions: evidence from fifty Japanese cities. Urban Clim 2:55–67. doi:10.1016/j.uclim.2012.10.006

Newman PWG, Kenworthy JR (1989) Gasoline consumption and cities—a comparison of U.S. cities with a global survey. J Am Plan Assoc 55:24–37

Newman PWG, Kenworthy JR (2006) Urban design to reduce automobile dependence. Opolis 2:35–52

Norman J, MacLean HL, Kennedy CA (2006) Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions. J Urban Plan Dev 132:10–21

Petterson D (2010) Bounding Containers; ArcGIS Resource Center. http://resources.arcgis.com/de/gallery/file/geoprocessing/details?entryID=3D230972-1422-2418-34A5-2F3FFF97C238. Accessed 22 Nov 2013

R Development Core Team (2012) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Rempel RS, Kaukinen D, Carr AP (2012) Patch Analyst and Patch Grid. Ontario Ministry of Natural Resources. Centre for Northern Forest Ecosystem Research, Thunder Bay

Rickwood P, Glazebrook G, Searle G (2008) Urban structure and energy—a review. Urban Policy Res 26:57–81. doi:10.1080/08111140701629886

Rosenberg M (2014) CBD: the CBD or Central business district is the core of the city. In: About. http://geography.about.com/od/urbaneconomicgeography/a/cbd.htm. Accessed 15 Oct 2014

RWI, Difu, NEA, PRAC (2010) Second State of European Cities Report. 191

Schneider A, Woodcock CE (2008) Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information. Urban Stud 45:659–692. doi:10.1177/0042098007087340

Schwarz N (2010) Urban form revisited-Selecting indicators for characterising European cities. Landsc Urban Plan 96:29–47. doi:10.1016/j.landurbplan.2010.01.007

SIRS (2011) Urban Atlas: delivery of land use/cover maps of major European urban agglomerations—Final report. 96

Spiekermann K (1997) Berufspendler—Trennung von Wohnort und Arbeitsort. In: Institut für Länderkunde (ed) Atlas Bundesrepublik Deutschland—Pilotband. IFL, Leipzig, pp 92–93

Strohbach MW, Haase D (2012) Above-ground carbon storage by urban trees in Leipzig, Germany: analysis of patterns in a European city. Landsc Urban Plan 104:95–104. doi:10.1016/j.landurbplan.2011.10.001

Strohbach MW, Arnold E, Haase D (2012) The carbon footprint of urban green space—a life cycle approach. Landsc Urban Plan 104:220–229. doi:10.1016/j.landurbplan.2011.10.013

Taubenböck H, Klotz M, Wurm M, Schmieder J, Wagner B, Wooster M, Esch T, Dech S (2013) Delineation of central business districts in mega city regions using remotely sensed data. Remote Sens Environ 136:386–401. doi:10.1016/j.rse.2013.05.019

The World Bank Group (2014) Urban population. In: Data Urban Popul. Total. http://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS/countries?display=graph. Accessed 26 Sep 2014

UNFCCC United NF on CC (2007) GHG inventories. http://unfccc.int/resource/cd_roms/na1/ghg_inventories/index.htm. Accessed 27 Sep 2014

United Nations Human Settlement Programme (2011) Cities and climate change. Earthscan, Washington

Viegas CV, Saldanha DL, Bond A, Ribeiro JLD, Selig PM (2013) Urban land planning: the role of a Master Plan in influencing local temperatures. Cities 35:1–13

Wang F, Chen C, Xiu C, Zhang P (2014) Location analysis of retail stores in Changchun, China: a street centrality perspective. Cities 41(Part A):54–63. doi:10.1016/j.cities.2014.05.005

Weber N, Haase D, Franck U (2014) Zooming into temperature conditions in the city of Leipzig: How do urban built and green structures influence earth surface temperatures in the city? Sci Total Environ 496:289–298. doi:10.1016/j.scitotenv.2014.06.144

Zhang L, Yang Z, Liang J, Cai Y (2010) Spatial variation and distribution of urban energy consumptions from cities in China. Energies 4:26–38. doi:10.3390/en4010026

Zhao C, Fu G, Liu X, Fu F (2011) Urban planning indicators, morphology and climate indicators: a case study for a north-south transect of Beijing, China. Build Environ 46:1174–1183. doi:10.1016/j.buildenv.2010.12.009