The impact of urban configuration types on urban heat islands, air pollution, CO_2 emissions, and mortality in Europe: a data science approach

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Summary

Background The world is becoming increasingly urbanised. As cities around the world continue to grow, it is important for urban planners and policy makers to understand how different urban configuration patterns affect the environment and human health. However, previous studies have provided mixed findings. We aimed to identify European urban configuration types, on the basis of the local climate zones categories and street design variables from Open Street Map, and evaluate their association with motorised traffic flows, surface urban heat island (SUHI) intensities, tropospheric NO_2, CO_2 per person emissions, and age-standardised mortality.

Methods We considered 946 European cities from 31 countries for the analysis defined in the 2018 Urban Audit database, of which 919 European cities were analysed. Data were collected at a 250 m×250 m grid cell resolution. We divided all cities into five concentric rings based on the Burgess concentric urban planning model and calculated the mean values of all variables for each ring. First, to identify distinct urban configuration types, we applied the Uniform Manifold Approximation and Projection for Dimension Reduction method, followed by the k-means clustering algorithm. Next, statistical differences in exposures (including SUHI) and mortality between the resulting urban configuration types were evaluated using a Kruskal–Wallis test followed by a post-hoc Dunn's test.

Findings We identified four distinct urban configuration types characterising European cities: compact high density (n=246), open low-rise medium density (n=245), open low-rise low density (n=261), and green low density (n=167). Compact high density cities were a small size, had high population densities, and a low availability of natural areas. In contrast, green low density cities were a large size, had low population densities, and a high availability of natural areas and cycleways. The open low-rise medium and low density cities were a small to medium size with medium to low population densities and low to moderate availability of green areas. Motorised traffic flows and NO_2 exposure were significantly higher in compact high density and open low-rise medium density cities when compared with green low density and open low-rise low density cities. Additionally, green low density cities had a significantly lower SUHI effect compared with all other urban configuration types. Per person CO_2 emissions were significantly lower in compact high density cities compared with green low density cities. Lastly, green low density cities had significantly lower mortality rates when compared with all other urban configuration types.

Interpretation Our findings indicate that, although the compact city model is more sustainable, European compact cities still face challenges related to poor environmental quality and health. Our results have notable implications for urban and transport planning policies in Europe and contribute to the ongoing discussion on which city models can bring the greatest benefits for the environment, climate, and health.

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Introduction

Current and projected rapid urbanisation rates highlight the importance of cities and the urgent need to prioritise the creation of healthy and sustainable city environments.[1] Currently, 55% of the global population resides in urban areas, and this proportion is expected to reach 68% by 2050.[1] In Europe, 75% of the population already lives in cities, with the urbanisation rate predicted to rise to 84% by 2050.[2] Living in cities offers many advantages, such as improved access to services and infrastructure, higher employment and economic opportunities, and more social connections and networking.[3] However, urban dwellers also face escalating social and economic disparities, a sedentary lifestyle, and increased exposure to environmental stressors that negatively affect human health, including air and noise pollution, rising local

Research in context

Evidence before this study

We searched the PubMed and Google Scholar databases, without language restrictions, from database inception to Sept 1, 2023, for studies on the association between urban configuration, environment, and health. Our search terms were "cities" OR "urban" OR "urban areas" OR "urban form" OR "urban type" OR "urban morphology" OR "urban configuration" OR "urban environment" OR "built environment" AND "air pollution" OR "particulate matter" OR "nitrogen dioxide" OR "$PM_{2.5}$" OR "NO_2" OR "green space" OR "greenness" OR "tree cover" OR "heat" OR "urban heat island" OR "carbon emissions" OR "CO_2 emissions" OR "greenhouse gas emissions" OR "health" OR "health impacts" OR "health effects" OR "mortality" OR "morbidity" OR "disease". We included observational large-scale studies that analysed multiple cities (generally more than 50) in Europe and globally and assessed associations with environmental exposures, carbon emissions, or health, or a combination. We identified ten relevant studies. Four papers evaluated the relationship between urban configuration and air pollution, green spaces, and urban heat islands in Europe and on a global scale. Two additional studies explored the association between urban structure and carbon emissions in Europe. Furthermore, four papers evaluated the associations between urban form and health outcomes in Latin America, Europe, and globally. However, these studies provided mixed findings, with some outlining the positive effects of compact urban configurations, and others estimating negative effects. Additionally, none of these studies integrated all four dimensions of urban configuration, environment, climate, and health.

Added value of this study

This study uniquely integrates the urban configuration, environment, climate, and health dimensions, making a substantial contribution to the ongoing discussion regarding which city model can provide the greatest benefits to the environment, sustainability, and health. Recent literature has highlighted the compact city model as the way forward to promote healthier and more sustainable urban environments. However, this study outlines that European compact cities tend to have poorer air quality, less green space, higher local land surface temperatures, and increased mortality rates compared with their lower density counterparts. These findings suggest that present-day compact cities in Europe might be in a transitional phase, combining positive attributes such as proximity to services and reduced carbon emissions with ongoing challenges such as densification, green space provision, mobility, and traffic management.

Implications of all the available evidence

Adding to previous literature, this study advocates for a comprehensive and multifaceted approach to optimise compact cities, recognising the need for a combination of strategic measures. The study proposes and discusses a set of key strategies, including medium to high dwelling density, diversification of local destinations, promotion of active transportation modes, reduction of private motorised traffic, and strategic integration of green space, as essential measures to enhance the benefits of compact urban configurations. This study also underscores the importance of strategies tailored to the specific context of each city, emphasising collaboration among diverse stakeholders to effectively address challenges and foster healthier and more sustainable urban development.

temperatures, and the depletion of green spaces.[3] In addition, cities account for approximately 75% of worldwide CO_2 emissions, significantly contributing to the intensification of global warming.[4]

To foster a sustainable and health-centric urban design, the compact city model has emerged as a potential solution. Compact cities are characterised by a greater density and shorter travel distances than sprawling cities, mixed land use, destination accessibility, and shorter distances to public transport.[5] This layout encourages more walking, cycling, and public transport use, leading to higher physical activity and decreased air and noise pollution and reduced per person carbon emissions.[5] Additionally, compact cities promote social interactions and a stronger sense of community among residents, contrasting with urban sprawl, which is linked to urban fragmentation, increased infrastructure costs, and socioeconomic inequalities.[5,6]

At the policy level, there is a growing recognition that the spatial configuration of cities can significantly influence sustainable development and population health through its effect on the natural environment, social context, and human behaviour. City leaders across Europe are in the process of implementing sustainability or climate measures, or both, as part of the EU's Green Deal, the Paris Climate Agreement, or voluntary commitments taken by city networks (such as the C40 Mayors' Agenda for a Green and Just Recovery or the Covenant of Mayors).[7–10]

However, despite these efforts, previous studies have shown that cities in Europe still face considerable exposure to adverse environmental exposure and a high premature mortality burden due to high ambient air pollution, road traffic noise, urban heat islands, and insufficient access to green spaces.[11–14] Similarly, one 2021 study indicated that the mitigation targets set for average greenhouse gas emissions across European cities fell short in aligning with the requirements of the Paris Agreement.[15] Urgent measures aimed at reducing adverse environmental exposures and greenhouse gas emissions are needed. Therefore, understanding the intricate relationship between urban configuration, environmental exposures, carbon emissions, and health is of crucial importance for urban planners and policy makers.

We built our study upon previous work by Taubenböck and colleagues,[16] which identified city types on the basis of intraurban morphological configurations, using a sample of 110 cities worldwide. The authors used the local climate zones (LCZs) classification scheme, which provides a harmonised description of urban form, and grouped the majority of European cities within the same city type.[16] This framework has been widely used as a highly versatile urban form zoning method, which can easily analyse urban characteristics and compare multiple cities under a unified standard.[16,17]

In this study, we focused on European cities and defined urban configuration, on the basis of available data, as the combination of intraurban morphological configurations, according to the built and natural categories of LCZs, and street design, according to road typologies from the Open Street Map (OSM) database. Our aim was to identify European urban configuration types and provide a descriptive analysis of potential associations with motorised traffic flows, urban heat island (UHI) intensities, and air pollution, based on surface UHI (SUHI) and tropospheric NO_2 proxies and CO_2 per person emissions. In addition, we sought to evaluate the associations between urban configuration types and age-standardised natural-cause mortality rates. Our extensive database of European cities allowed us to disentangle relationships at the European level, shedding light on the associations between urban configuration, levels of environmental exposures, CO_2 emissions, and health, and providing more detailed information on how these urban features are inter-related in Europe.

Methods

European cities and data collection

Our analysis focused on European cities listed in the Urban Audit dataset 2018,[18] which uses the city definition as set out by the Organization for Economic Cooperation and Development European Commission, which is based on population density and local administrative boundaries (appendix 1 p 2).[19] Overall, we considered 946 European cities (from 31 countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Germany, Estonia, Finland, France, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the UK) for the analysis from the Urban Audit database (appendix 2). We collected all data at a 250 m×250 m grid cell resolution based on the Global Human Settlement Layer population dataset for 2015,[20] following the same data collection procedure as in our previous studies (appendix 1 p 2).[11–14]

We evaluated the intraurban morphological configurations of European cities using the LCZs classification, which provides a universal and standardised description of urban form.[21] The LCZ scheme is based on satellite imagery and classifies urban landscapes considering building density and height, imperviousness, and vegetation variables into 17 LCZs, ten of these representing the built types of urban areas (compact high-rise, compact mid-rise, compact low-rise, open high-rise, open mid-rise, open low-rise, lightweight low-rise, large low-rise, sparsely built, and heavy industry) and seven representing the non-built or natural types of urban areas (dense trees, scattered trees, bush or scrub, low plants, bare rock or paved, bare soil or sand, and water; appendix 1 p 4).[21] For this study, we retrieved the LCZ classification developed by Demuzere and colleagues,[22] in which every 100 m×100 m in Europe was assigned an LCZ. We overlaid the LCZ layer with our 250 m grid cell layer and estimated the proportion of area corresponding to each LCZ for each of the grid cells.

To evaluate the street design, we retrieved the density of distinct road typologies from the OSM database. We included road types as follows: motorised roads (classified as either motorway or trunk), primary roads, secondary roads, tertiary roads, residential roads (classified as either unclassified, residential, or living streets), pedestrian zones, and cycleways (appendix 1 p 9). For each grid cell, we calculated the length in metres of each road type.

For the **OSM database** see https://www.openstreetmap.org/

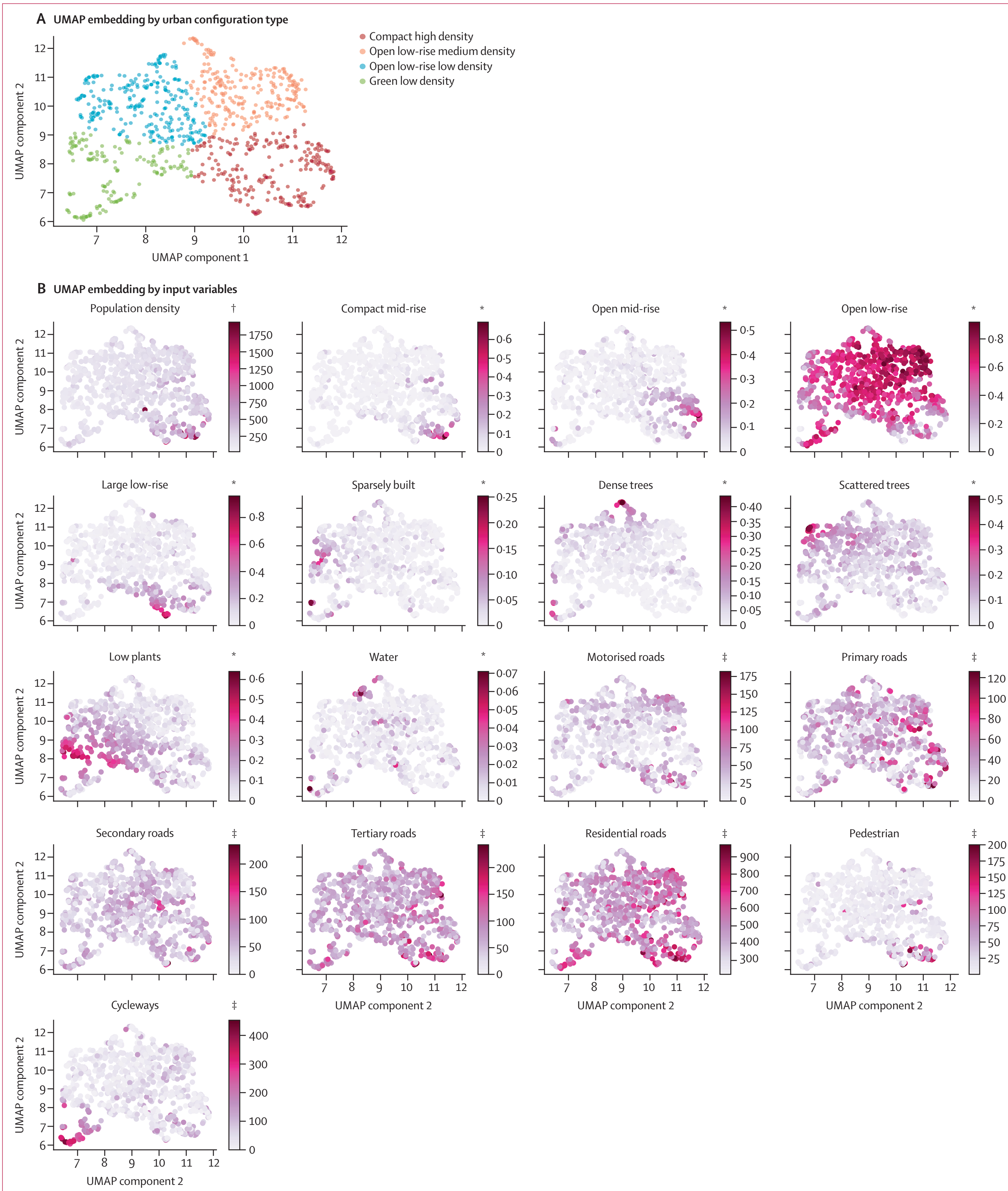
Traffic volume data were retrieved from the OTM database, which details the vehicle per day counts for major roads. To estimate the traffic volume within each grid cell, we aggregated the traffic counts from all roads that intersected each grid cell. Subsequently, to account for variations in road length across grid cells, we calculated a weighted average as follows: grid traffic volume=(grid road length in km×traffic volume)/road length in km. The resulting variable represented the vehicles per day per km of road within each grid cell.

For the **OTM database** see https://opentransportmap.info/

We assessed the UHI effect on the basis of the SUHI indicator, defined as the higher land surface temperature (LST) in cities compared with surrounding rural areas.[23] To estimate the LST in cities, we retrieved Landsat-8 images[24] for 2015 at a 30 m×30 m resolution and estimated the median summer (from June 1 to August 31) LST for each grid cell. To define the surrounding rural area, we took a buffer zone of 6 km surrounding each city, to ensure sufficient coverage, and defined the rural area on the basis of the Coordination of Information on the Environment Land Cover (CORINE) agricultural, forest, and natural areas categories (appendix 1 p 15). To estimate the average rural LST for each city, we calculated the median summer LST for each of the rural grid cells and afterwards averaged the LST for the whole rural area. The SUHI was estimated as the difference between the average of all median summer rural LST and the median summer LST recorded in each urban grid cell.

See **Online** for appendix 1

See **Online** for appendix 2


A UMAP embedding by urban configuration type
Compact high density
Open low-rise medium density
Open low-rise low density
Green low density
UMAP component 1
UMAP component 2
B UMAP embedding by input variables
Population density †
Compact mid-rise *
Open mid-rise *
Open low-rise *
Large low-rise *
Sparsely built *
Dense trees *
Scattered trees *
Low plants *
Water *
Motorised roads ‡
Primary roads ‡
Secondary roads ‡
Tertiary roads ‡
Residential roads ‡
Pedestrian ‡
Cycleways ‡

For air pollution, we used as our exposure proxy the annual mean tropospheric NO_2 vertical column densities, which constitute a tracer of anthropogenic emissions.[25] This exposure proxy is suitable to delineate urban pollution islands and it is not influenced by any modelling assumptions on emissions or land use.[25] Data were retrieved using satellite remote sensing from TROPOMI[26] for 2019, which has daily global coverage at a resolution of $3\cdot5\times5\cdot5$ km^2. To estimate annual tropospheric NO_2, all daily satellite overpasses were oversampled over a 100 m×100 m grid cell resolution (appendix 1 p 17). We overlaid the NO_2 layer with our 250 m grid cell layer and calculated the mean annual tropospheric NO_2 in µmoL per m^2 for each grid cell. To validate the NO_2 proxy, we used NO_2 measurements from official monitoring stations, available through the European Air Quality e-Reporting system.[27]

We retrieved CO_2 emissions data from the open-source Data Inventory for Anthropogenic CO_2,[28] which provides CO_2 emissions from fossil fuel combustion at 1 km×1 km resolution for 2019. In this dataset, national emissions are spatialised on the basis of satellite night-time light data and power plant location and profiles.[28] To estimate the per person emissions, we overlaid the CO_2 emissions layer with the 250 m grid cell layer and distributed the CO_2 emissions proportionally on the basis of the intersecting area of the 250 m grid cells with the 1 km grid cells (appendix 1 p 20). We divided the emissions between the population in each 250 m grid cell to obtain the CO_2 per person emissions in metric tons. To verify the CO_2 metric, we additionally explored the CO_2 emissions reported in the Copernicus Atmosphere Monitoring Service regional inventory for the residential and transport sectors.[29]

Finally, given that previous studies have indicated associations between urban environment features and health outcomes,[30–33] we sought to assess potential differences in adult age-standardised natural-cause mortality rates between the urban configuration types. Natural-cause mortality rates were retrieved at the city level from our previous studies on the health effects of environmental exposures in European cities, estimated on the basis of data from the Eurostat city database for 2015 (appendix 1 p 50).[11,12] Natural-cause mortality was used due to the absence of data on more specific health outcomes (such as morbidity or traffic injuries) for the large number of European cities in the analysis.

Figure 1: **UMAP embedding coloured by urban configuration type (A) and by each input variable (B)**

UMAP component 1 and 2 refer to the two relative dimensions to which the UMAP algorithm reduced the data. Each dot in the plot represents a city, and dots closer to each other represent cities that have more similar features in terms of local climate zone and road typologies. UMAP=Uniform Manifold Approximation and Projection for Dimension Reduction. *Percentage. †Mean population per grid cell. ‡Mean meters per grid cell.

Data analysis

To analyse the spatial distribution of the variables in a harmonised manner for all European cities, we divided all cities into five rings on the basis of the Burgess concentric urban planning model.[34] For each city, we extracted the urban centre coordinates from the OSM Nominatim database[35] and calculated the distance from the urban centre to the centroid of each of the grid cells. We divided the cities into rings on the basis of the quintile distribution of grid cell distances to the urban centres (appendix 1 p 3). Accordingly, we grouped all grid cells within each city by ring and calculated the mean values of all variables for further analyses.

To identify and characterise distinct urban configuration types, we applied the Uniform Manifold Approximation and Projection for Dimension Reduction (UMAP) method, followed by the k-means clustering algorithm. UMAP is a novel non-linear dimension reduction algorithm able to learn the manifold structure of large input datasets and produce a low-dimensional embedding that preserves the basic topological structure of the manifold.[36] We used LCZs and OSM variables from each of the five rings for each city as input data for the UMAP algorithm (appendix 1 pp 22–25). Only cities with complete datasets were considered for the analysis, resulting in a sample of 919 cities. The resulting UMAP embedding was evaluated on the basis of the distribution of the input variables and used as input for the k-means clustering algorithm to identify the urban configuration types. To select the optimal number of clusters we applied the Elbow method and set the number at k=4 (appendix 1 p 25).

Finally, we evaluated statistical differences in traffic volume, SUHI intensity, NO_2 exposure, CO_2 emissions, and natural-cause mortality between the resulting urban configuration types. Given that the SUHI intensity and mortality rates did not comply with the homogeneity of variance assumption, and traffic volume, NO_2, and CO_2 emissions were not normally distributed, we applied the Kruskal–Wallis test, followed by the post-hoc Dunn's test. In all cases, given the variability in exposure and emissions between the city rings, differences in these variables were evaluated for each ring separately. All analyses were conducted using Python version 3.9.6.

Sensitivity analyses

We conducted sensitivity analyses related to SUHI intensity, given that numerous approaches exist to estimate SUHI, and that it is influenced by other factors in addition to urban configuration, such as geographical location and climatic conditions.[37] For instance, in semi-arid regions, rural surfaces might be warmer than urban areas, especially when vegetation has not been irrigated due to droughts, restricting the evapotranspiration rate.[38] As a result, Mediterranean cities might present a lower SUHI than expected. To assess this effect and avoid misleading conclusions, first, we compared the SUHI between

	Compact high density (n=246)			Open low-rise medium density (n=245)			Open low-rise low density (n=261)			Green low density (n=167)		
	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR
City area, km²	126 (9·8)	83	41–148	129 (12)	81	43–143	202 (11·6)	148	83–259	381 (41·8)	206	108–352
City population, number	276 815 (28 874)	139586	73 644–244 439	229 016 (36 089)	135 247	84 426–242 533	147 738 (9330)	106 277	74 024–173 973	164 518 (13 232)	117 287	82 521–176 973
Population density (mean population per grid cell)												
Whole city	421 (19·5)	330	240–450	248 (5·9)	237	193–289	173 (3·8)	172	131–205	179 (6·4)	158	119–221
Ring 0	589 (22·4)	482	354–703	359 (9·7)	324	260–423	280 (6·5)	269	220–312	334 (11·7)	297	236–390
Ring 1	496 (21·3)	391	284–552	275 (7·3)	260	206–322	193 (4·9)	187	144–238	208 (8·4)	188	133–265
Ring 2	419 (20·8)	311	225–469	230 (6·0)	223	178–274	153 (4·4)	152	102–192	143 (7·1)	123	71–195
Ring 3	346 (19·7)	246	172–384	207 (5·9)	203	146–258	129 (4·1)	128	76–169	114 (6·1)	87	52–163
Ring 4	252 (17·5)	174	109–269	170 (5·5)	158	108–221	107 (4·2)	95	59–141	95 (5·5)	72	42–126
Compact mid-rise (%)												
Whole city	8·7 (0·8)	3·7	0·5–11·0	2·1 (0·2)	0·6	0·0–2·7	1 (0·1)	0·1	0·0–1·2	1·9 (0·3)	0·3	0·0–1·7
Ring 0	25·4 (1·7)	15·8	2·5–42·5	8·6 (0·9)	2·5	0·0–11·8	4·3 (0·5)	0·4	0·0–4·8	8·5 (1·2)	1·4	0·0–8·2
Ring 1	9·1 (1·1)	0·4	0·0–9·2	1·3 (0·3)	0·0	0·0–0·1	0·3 (0·1)	0·0	0·0–0·0	0·7 (0·2)	0·0	0·0–0·0
Ring 2	4·3 (0·7)	0·0	0·0–2·1	0·4 (0·1)	0·0	0·0–0·0	0·1 (0·1)	0·0	0·0–0·0	0·2 (0·1)	0·0	0·0–0·0
Ring 3	3·0 (0·6)	0·0	0·0–0·1	0·2 (0·1)	0·0	0·0–0·0	0·1 (0·0)	0·0	0·0–0·0	0·0 (0·0)	0·0	0·0–0·0
Ring 4	1·7 (0·5)	0·0	0·0–0·0	0·1 (0·0)	0·0	0·0–0·0	0·1 (0·0)	0·0	0·0–0·0	0·0 (0·0)	0·0	0·0–0·0
Open mid-rise (%)												
Whole city	10·8 (0·7)	8·9	1·6–17·1	2·7 (0·2)	1·3	0·2–4·0	1·6 (0·1)	0·5	0·1–2·0	1·9 (0·3)	0·3	0·0–1·5
Ring 0	20·8 (1·3)	15·7	0·8–36·5	8·3 (0·7)	3·7	0·3–13·4	5·2 (0·5)	1·5	0·0–6	5·0 (0·7)	0·9	0·0–5·8
Ring 1	15·2 (1·1)	9·1	0·8–25·4	2·5 (0·3)	0·4	0·0–3·2	1·3 (0·2)	0·0	0·0–1·2	2·1 (0·4)	0·0	0·0–0·7
Ring 2	9·8 (0·9)	5·0	0·2–13·2	1·3 (0·2)	0·1	0·0–1·3	0·6 (0·1)	0·0	0·0–0·3	1·1 (0·3)	0·0	0·0–0·1
Ring 3	5·5 (0·6)	1·1	0·0–6·3	0·7 (0·1)	0·0	0·0–0·5	0·4 (0·1)	0·0	0·0–0·0	0·8 (0·3)	0·0	0·0–0·0
Ring 4	2·6 (0·4)	0·0	0·0–2·4	0·4 (0·1)	0·0	0·0–0·1	0·2 (0·1)	0·0	0·0–0·0	0·5 (0·2)	0·0	0·0–0·0
Open low-rise (%)												
Whole city	42·8 (1·2)	46·2	32·6–56·3	69·1 (0·8)	70·6	62·8–72·0	57·2 (0·7)	58·8	51·5–65·3	44·5 (1·4)	46·7	33·3–57·9
Ring 0	25·3 (1·4)	21·3	6·2–39·7	62·3 (1·3)	64·3	50·4–78·2	67·9 (1)	70·8	59·0–80·7	53·7 (2·1)	58·9	30·7–78·8
Ring 1	43·4 (1·6)	44·2	22·0–64·6	75·8 (0·9)	78·0	68·3–86·0	69 (0·9)	71·7	61·2–79·3	56·3 (1·7)	60·2	43·9–74·8
Ring 2	49·9 (1·5)	55·2	34·1–69·3	74·9 (0·9)	77·2	68·0–84·6	59·7 (0·9)	60·9	51·4–70·3	45·7 (1·7)	46·2	30·5–62·9
Ring 3	51·2 (1·4)	57·1	38·9–68	71·3 (0·9)	72·1	64·0–80·9	50·9 (1·1)	52·9	41·8–62·5	37·5 (1·6)	40·5	21·9–51·7
Ring 4	44·3 (1·3)	45·8	30·9–59·8	61·5 (1·2)	63·0	52·6–74·5	38·6 (1·1)	39·7	25·8–50·9	29·2 (1·5)	27·1	13·7–43·2
Large low-rise (%)												
Whole city	17·8 (1·2)	11·0	4·5–26·1	4·7 (0·3)	3·0	1·3–5·5	3·3 (0·3)	2·1	0·8–4·3	6·7 (0·5)	4·1	1·8–10·0
Ring 0	22·9 (1·7)	11·1	3·9–32·4	9·9 (0·8)	5·0	0·9–13·9	8 (0·7)	4·2	1·0–10·8	15·5 (1·5)	7·6	2·9–22·6
Ring 1	21·5 (1·6)	11·9	3·3–31·9	5·3 (0·4)	2·9	0·8–6·3	3·8 (0·4)	2·0	0·3–4·8	8·7 (0·9)	4·6	1·4–11·9
Ring 2	19·3 (1·4)	9·2	3·5–26·9	3·3 (0·3)	1·4	0·3–3·6	2·3 (0·3)	1·0	0·1–2·9	4·4 (0·5)	2·1	0·3–6·0
Ring 3	15·3 (1·3)	7·1	1·5–20·1	2·8 (0·3)	1·1	0·1–2·9	1·4 (0·2)	0·3	0·0–1·6	2·4 (0·3)	1·0	0·0–3·1
Ring 4	9·9 (1·1)	2·5	0·1–11·5	2·1 (0·3)	0·5	0·0–2·1	1·1 (0·2)	0·0	0·0–0·6	2·5 (0·5)	0·3	0·0–2·9

(Table 1 continues on next page)

	Compact high density (n=246)			Open low-rise medium density (n=245)			Open low-rise low density (n=261)			Green low density (n=167)		
	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR
(Continued from previous page)												
Sparsely built (%)												
Whole city	0·8 (0·1)	0·3	0·0–1·2	1·0 (0·1)	0·4	0·1–1·3	2·8 (0·2)	1·8	0·5–3·9	2·7 (0·3)	1·4	0·4–3·3
Ring 0	0·1 (0·0)	0·0	0·0–0·0	0·3 (0·1)	0·0	0·0–0·1	0·5 (0·1)	0·0	0·0–0·4	0·8 (0·2)	0·0	0·0–0·6
Ring 1	0·3 (0·0)	0·0	0·0–0·1	0·7 (0·1)	0·0	0·0–0·6	1·3 (0·2)	0·4	0·0–1·2	1·9 (0·4)	0·6	0·0–2·0
Ring 2	0·5 (0·1)	0·0	0·0–0·4	0·9 (0·1)	0·2	0·0–0·8	2·3 (0·2)	1·1	0·0–3·5	2·9 (0·4)	0·9	0·0–3·2
Ring 3	0·7 (0·1)	0·0	0·0–0·8	1·3 (0·1)	0·3	0·0–1·5	3·7 (0·3)	1·8	0·4–4·8	3·8 (0·4)	1·6	0·2–5·0
Ring 4	2·5 (0·3)	0·5	0·0–2·7	2·0 (0·2)	0·7	0·1–2·9	6·0 (0·5)	3·6	1·2–8·8	4·0 (0·4)	2·0	0·5–5·7
Dense trees (%)												
Whole city	1·9 (0·2)	0·7	0·0–3·1	5·1 (0·4)	2·7	0·8–6·4	4·6 (0·2)	3·7	1·8–6·7	3·5 (0·4)	1·3	0·1–3·9
Ring 0	0·3 (0·1)	0·0	0·0–0·3	1·9 (0·2)	0·5	0·0–1·9	2·0 (0·2)	0·8	0·1–2·5	1·4 (0·2)	0·1	0·0–1·1
Ring 1	0·9 (0·1)	0·0	0·0–1·2	4·1 (0·5)	1·4	0·2–4·7	3·8 (0·3)	2·4	0·7–5·1	3·0 (0·5)	0·6	0·0–2·9
Ring 2	1·7 (0·2)	0·1	0·0–2·4	5·4 (0·5)	2·1	0·5–6·8	4·8 (0·3)	3·6	1·2–6·9	3·8 (0·5)	0·9	0·0–4·3
Ring 3	2·7 (0·3)	0·5	0·0–4·0	6·1 (0·5)	2·9	1·0–7·9	5·6 (0·3)	4·2	1·8–8·3	4·5 (0·6)	1·6	0·0–4·9
Ring 4	3·8 (0·4)	1·1	0·0–6·1	8·1 (0·7)	4·0	1·0–10·4	7·1 (0·4)	5·3	2·0–10·0	4·6 (0·6)	1·5	0·1–5·2
Scattered trees (%)												
Whole city	5·6 (0·3)	4·6	1·8–8·2	8·1 (0·3)	7·6	5·2–10·3	14·1 (0·5)	12·3	8·2–17·6	7·6 (0·4)	7·4	4·5–10·6
Ring 0	1·8 (0·1)	0·8	0·0–2·7	3·5 (0·2)	3·0	1·1–5·0	5·9 (0·3)	5·0	2·6–8·8	3·1 (0·2)	2·2	0·8–4·5
Ring 1	4·0 (0·3)	2·7	0·6–6·1	6·4 (0·3)	5·8	3·4–8·9	12·1 (0·5)	10·4	6·7–15·1	7·2 (0·4)	6·0	2·9–9·9
Ring 2	5·7 (0·4)	4·4	1·3–9·0	8·5 (0·4)	7·7	4·3–11·1	15·4 (0·7)	12·8	8·5–19·8	8·5 (0·5)	8·2	3·8–11·8
Ring 3	6·8 (0·4)	4·9	1·9–10·2	9·9 (0·4)	9·0	5·6–13·1	17·5 (0·8)	14·7	8·5–23·2	9·1 (0·5)	8·3	3·6–13·2
Ring 4	9·7 (0·6)	6·8	2·9–13·9	12·3 (0·6)	10·2	6·4–16·2	19·7 (0·9)	16·5	9·4–25·9	10·1 (0·6)	8·4	3·8–13·8
Low plants (%)												
Whole city	9·8 (0·4)	9·4	3·8–14·7	5·3 (0·3)	4·7	2·2–8	13·5 (0·5)	13·8	8·1–18·7	27·4 (1·1)	27·8	17·0–36·9
Ring 0	0·8 (0·1)	0·1	0·0–0·9	0·7 (0·1)	0·1	0·0–0·8	2·2 (0·2)	1·0	0·2–2·6	3·9 (0·4)	1·9	0·5–5·4
Ring 1	3·7 (0·3)	2·0	0·4–5·2	2·2 (0·2)	1·0	0·3–3·1	7·2 (0·4)	5·1	2·4–9·9	17·1 (1·2)	13·9	5·3–25·8
Ring 2	7·3 (0·4)	5·5	1·6–11·5	4·4 (0·3)	2·7	1·0–6·9	13·8 (0·6)	12·3	5·7–19·6	31·1 (1·6)	30·5	13·3–46·1
Ring 3	13·2 (0·7)	11·1	3·8–20·1	6·8 (0·4)	5·1	1·7–10·7	19·0 (0·7)	17·8	9·9–26·9	39·3 (1·7)	40·2	21·9–53·9
Ring 4	23·7 (1·1)	22·0	9·1–36	12·5 (0·7)	10·2	3·5–19·4	25·3 (1·0)	24·5	13·2–35·4	45·6 (1·6)	47·3	30·0–61·7
Water (%)												
Whole city	0·5 (0·0)	0·2	0·0–0·8	0·5 (0·0)	0·3	0·1–0·6	0·7 (0·1)	0·3	0·1–0·7	0·7 (0·1)	0·4	0·1–1·0
Ring 0	0·7 (0·1)	0·0	0·0–0·9	0·7 (0·1)	0·2	0·0–0·8	1·0 (0·1)	0·2	0·0–0·8	0·9 (0·1)	0·3	0·0–1·2
Ring 1	0·5 (0·0)	0·1	0·0–0·7	0·5 (0)	0·2	0·0–0·6	0·7 (0·1)	0·2	0·0–0·7	0·6 (0·1)	0·2	0·0–0·7
Ring 2	0·4 (0·0)	0·0	0·0–0·5	0·4 (0·1)	0·1	0·0–0·4	0·5 (0·1)	0·1	0·0–0·5	0·6 (0·1)	0·2	0·0–0·7
Ring 3	0·4 (0·0)	0·1	0·0–0·6	0·4 (0)	0·1	0·0–0·5	0·6 (0·1)	0·1	0·0–0·6	0·7 (0·1)	0·2	0·0–0·9
Ring 4	0·5 (0·1)	0·1	0·0–0·7	0·5 (0·1)	0·1	0·0–0·7	0·9 (0·1)	0·2	0·0–0·7	0·9 (0·1)	0·3	0·0–1·2

(Table 1 continues on next page)

	Compact high density (n=246)			Open low-rise medium density (n=245)			Open low-rise low density (n=261)			Green low density (n=167)		
	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR
(Continued from previous page)												
Motorised roads (mean metres per grid cell)												
Whole city	25 (1·7)	17	3–37	30 (1·4)	29	11–42	22 (1·1)	20	8–33	21 (1·3)	20	9–29
Ring 0	11 (1·6)	0	0–8	30 (2·3)	15	0–53	24 (1·9)	10	0–37	19 (2·1)	3	0–30
Ring 1	22 (2·3)	3	0–31	31 (2·1)	24	1–47	29 (1·8)	26	0–43	27 (2·2)	20	1–40
Ring 2	30 (2·7)	15	0–42	30 (1·7)	26	7–44	24 (1·4)	19	3–38	26 (2·0)	22	7–36
Ring 3	32 (3·1)	16	0–41	30 (1·8)	24	10–44	19 (1·2)	16	3–29	18 (1·4)	15	4–25
Ring 4	29 (3·1)	14	0–38	30 (2·0)	23	6–43	16 (1·2)	12	0–24	18 (1·5)	12	5–25
Primary roads (mean metres per grid cell)												
Whole city	36 (1·7)	33	17–51	34 (1·3)	33	19–47	29 (1·0)	29	16–40	25 (1·2)	25	13–36
Ring 0	50 (3·1)	42	0–77	53 (2·5)	50	22–77	46 (2·1)	49	15–72	41 (2·9)	36	5–67
Ring 1	43 (2·5)	38	12–62	38 (1·9)	31	18–51	30 (1·3)	27	16–42	29 (1·9)	27	7–41
Ring 2	35 (2·0)	28	12–53	31 (1·8)	25	12–47	24 (1·0)	23	11–35	23 (1·6)	21	6–34
Ring 3	31 (1·8)	24	8–48	25 (1·4)	22	8–35	22 (1·1)	18	9–31	18 (1·3)	15	4–27
Ring 4	23 (1·6)	17	2–34	24 (1·5)	21	5–38	23 (1·4)	18	6–31	15 (1·2)	12	2–24
Secondary roads (mean metres per grid cell)												
Whole city	50 (2·1)	48	32–64	48 (1·7)	47	28–63	40 (1·3)	38	25–52	45 (1·6)	44	32–57
Ring 0	76 (3·4)	76	36–105	72 (3·2)	68	35–101	58 (2·4)	52	28–86	77 (2·9)	80	56–101
Ring 1	58 (2·6)	52	29–80	50 (2·2)	46	23–68	40 (1·7)	36	21–53	49 (2·4)	44	25–68
Ring 2	49 (2·8)	39	20–65	43 (1·9)	40	21–58	37 (1·5)	34	19–50	36 (2·0)	33	19–48
Ring 3	38 (2·2)	33	12–51	40 (1·7)	38	21–55	33 (1·4)	29	17–47	32 (1·7)	28	18–45
Ring 4	31 (2·1)	25	8–43	36 (1·6)	34	16–51	33 (1·5)	30	13–46	32 (1·7)	30	15–47
Tertiary roads (mean metres per grid cell)												
Whole city	89 (2·6)	83	64–105	72 (2·0)	70	51–88	59 (1·3)	59	46–72	75 (2·4)	74	52–91
Ring 0	128 (4·0)	119	88–164	90 (2·9)	87	61–114	79 (2·5)	73	53–103	97 (3·5)	96	70–122
Ring 1	101 (3·3)	94	66–127	75 (2·6)	71	48–98	59 (1·7)	57	38–76	76 (2·9)	75	51–97
Ring 2	83 (3·1)	74	52–104	69 (2·5)	66	43–90	53 (1·7)	50	35–70	69 (2·9)	67	45–89
Ring 3	70 (3·3)	64	39–84	67 (2·3)	63	42–88	54 (1·6)	53	37–71	66 (2·8)	64	38–91
Ring 4	62 (2·8)	58	33–82	61 (2·2)	58	37–81	52 (1·6)	51	33–68	65 (2·9)	65	34–90
Residential roads (mean metres per grid cell)												
Whole city	535 (9·6)	498	419–635	520 (6·4)	512	445–589	439 (5·0)	437	381–492	463 (10·0)	442	352–559
Ring 0	681 (14·3)	649	498–829	613 (7·9)	590	525–682	570 (7·9)	551	486–633	669 (12·8)	681	541–792
Ring 1	592 (11·8)	568	452–706	536 (7·6)	523	453–604	476 (7·1)	465	403–542	515 (12·3)	496	393–646
Ring 2	538 (11·0)	499	417–637	504 (7·4)	505	422–583	423 (6·8)	407	348–487	421 (12·5)	386	303–542
Ring 3	474 (11·4)	428	345–557	497 (7·4)	493	415–574	386 (6·0)	383	321–448	379 (12·5)	341	261–483
Ring 4	399 (10·1)	374	284–485	449 (8·6)	436	350–534	346 (6·4)	339	275–405	339 (11·8)	303	242–397

(Table 1 continues on next page)

Mediterranean (n=206; appendix 1 pp 39–40) and non-Mediterranean (n=713) cities, including biome classification (ie, Alpine, Arctic, Atlantic, Black Sea, Boreal, Continental, Mediterranean, Pannonian, and Steppic), as defined by the European Environment Agency;[39] and, second, we excluded the Mediterranean cities when evaluating differences in SUHI intensity between the urban configuration types. In addition, we also explored an alternative method to estimate the SUHI intensity—namely, the simplified urban extent algorithm developed by Chakraborty and Lee.[40] In this approach, the SUHI is defined as the LST difference between urban and non-urban land uses within the same city boundary, rather than the LST difference with the adjacent rural area.

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The funders of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Of the 919 European cities included in this study, the LCZ built types were more prevalent in the central rings of the analysed cities and their share decreased towards the peripheral rings, whereas the LCZ natural categories increased towards the outskirts of the cities (appendix 1 pp 4–8). Overall, the open low-rise built type was the most common category among European cities (appendix 1 pp 4–8). The density of motorised roads was slightly higher in the outskirts of the cities, whereas all other road types and cycleways had a decreasing density from the central rings to the outskirts (appendix 1 pp 9–12). We observed higher traffic volume in the city centres compared with the outskirts (appendix 1 pp 13–14). Similarly, the SUHI intensity was higher in the city centres, ranging from a mean of 2·1°C to 4·2°C (appendix 1 pp 15–16). Tropospheric NO_2 had slightly higher values in the central rings, ranging from a mean of 53·1 to 56·7 μmol/m² in the periphery of the cities (appendix 1 pp 18–19). Lastly, the CO_2 per person emissions were higher towards the outskirts of the cities, varying between a mean of 0·8 and 1·9 metric tons (appendix 1 pp 20–21).

The UMAP embedding showed a continuum without a pronounced segregation of clusters, reflecting similarities in the structural composition of European cities (figure 1). After applying the k-means clustering algorithm, we identified four urban configuration types.

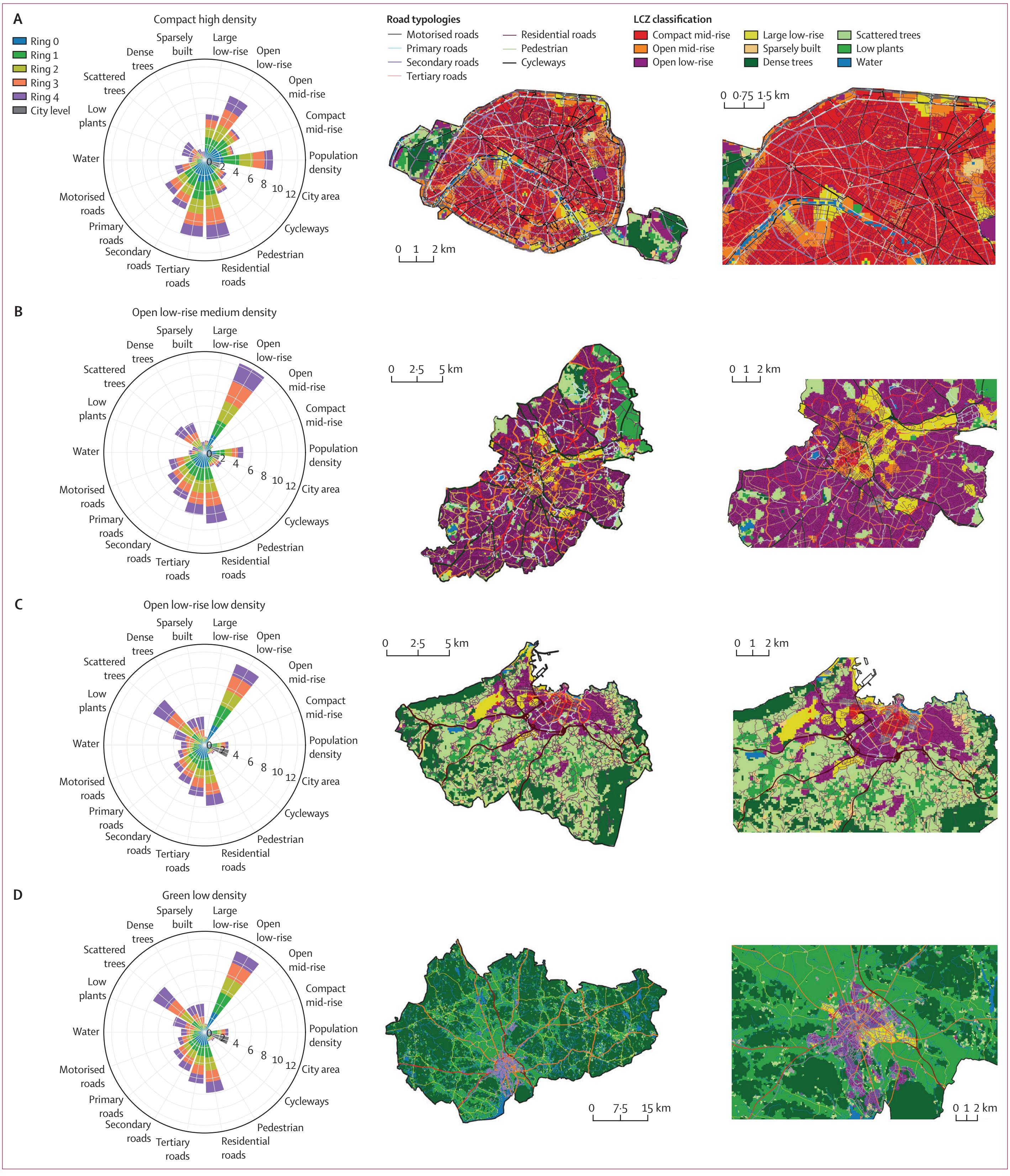
The first was compact high density cities (n=246), which were characterised by small city sizes and high population densities; compact mid-rise, open mid-rise, and large low-rise structures in the central rings; a high density of pedestrian areas; moderate cycleway density; and an overall low availability of natural areas (ie, dense trees, scattered trees, and low plants; table 1, figure 2A).

The second was open low-rise medium density cities (n=245), which were defined by small city sizes and medium population densities, open low-rise

	Compact high density (n=246)			Open low-rise medium density (n=245)			Open low-rise low density (n=261)			Green low density (n=167)		
	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR	Mean (SE)	Median	IQR
(Continued from previous page)												
Pedestrian (mean metres per grid cell)												
Whole city	33 (2·7)	16	9–40	14 (1·1)	10	5–15	9 (0·7)	6	4–11	15 (1·1)	10	5–20
Ring 0	73 (4·4)	50	27–98	38 (2·4)	27	16–46	28 (1·7)	20	11–34	41 (2·9)	29	16–56
Ring 1	36 (3·6)	13	4–33	12 (1·3)	5	1–13	7 (1·0)	3	1–7	14 (1·4)	7	2–17
Ring 2	27 (3·1)	8	2–28	9 (0·9)	4	1–10	4 (0·5)	2	0–5	9 (1·0)	3	0–12
Ring 3	20 (2·6)	4	1–16	7 (0·9)	3	1–8	3 (0·3)	1	0–4	6 (0·8)	2	0–7
Ring 4	12 (1·7)	2	0–9	5 (0·7)	2	0–6	3 (0·7)	1	0–2	6 (0·8)	1	0–7
Cycleways (mean metres per grid cell)												
Whole city	49 (2·8)	36	15–75	38 (2·2)	29	12–53	22 (1·2)	17	8–30	118 (8·8)	67	26–194
Ring 0	69 (4·1)	51	19–106	51 (3·1)	37	15–72	39 (2·5)	26	13–50	173 (10·9)	124	52–277
Ring 1	63 (3·9)	45	17–89	41 (2·7)	30	9–58	27 (1·6)	18	7–43	137 (9·5)	92	33–224
Ring 2	50 (3·4)	33	10–70	38 (2·7)	24	8–53	20 (1·4)	12	4–32	111 (9·4)	48	17–205
Ring 3	38 (3·2)	21	4–54	35 (2·5)	25	6–49	15 (1·1)	11	1–21	96 (9·4)	24	7–167
Ring 4	26 (2·4)	13	0–34	26 (1·9)	19	3–39	11 (0·9)	5	1–16	73 (7·9)	15	2–119

All cities were divided into five rings on the basis of the Burgess concentric urban planning model, with ring 0 being the innermost circle.

***Table 1:* Description of urban configuration types**


A
Compact high density
Ring 0
Ring 1
Ring 2
Ring 3
Ring 4
City level
Sparsely built
Large low-rise
Open low-rise
Open mid-rise
Compact mid-rise
Population density
City area
Cycleways
Pedestrian
Residential roads
Tertiary roads
Secondary roads
Primary roads
Motorised roads
Water
Low plants
Scattered trees
Dense trees
0
2
4
6
8
10
12
Road typologies
Motorised roads
Primary roads
Secondary roads
Tertiary roads
Residential roads
Pedestrian
Cycleways
LCZ classification
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Sparsely built
Dense trees
Scattered trees
Low plants
Water
0 1 2 km
0 0·75 1·5 km
B
Open low-rise medium density
0 2·5 5 km
0 1 2 km
C
Open low-rise low density
0 2·5 5 km
0 1 2 km
D
Green low density
0 7·5 15 km
0 1 2 km

configurations prevalent in all rings, higher motorised road density, intermediate pedestrian and cycleway density, and some availability of dense trees and scattered trees towards the city periphery (table 1; figure 2B).

The third was open low-rise low density cities (n=261), which were characterised by medium sizes and low population densities, open low-rise structures prevailing in the city centres, a low density of pedestrian areas and cycleways, and moderate to high availability of natural areas (ie, scattered trees and low plants) towards the outskirts of the cities (table 1; figure 2C).

And fourth was green low density cities (n=167), defined by large city sizes and low population densities, open low-rise configurations with their share decreasing towards the peripheral rings, moderate pedestrian density, high cycleway density, and high availability of natural areas (ie, low plants) already starting from the second ring, and increasing in subsequent rings (table 1; figure 2D).

Most of the population in all cities resided in compact high density (68 096 496/190 239 499 [35·8%]) and open low-rise medium density (56 108 876 [29·5%]) cities, compared with the open low-rise low density (38 559 619 [20·3%]) and green low density (27 474 508 [14·4%]) city types (table 1).

Traffic volume was significantly higher in compact high density cities for all rings compared with all other city types. The open low-rise medium density cities had significantly higher traffic volume than open low-rise low density and green low density cities in all rings (except ring 2), whereas these two types generally had non-significant differences between them (table 2; figure 3; appendix 1 pp 27–28).

The SUHI intensity was significantly lower among green low density cities compared with the open low-rise medium density and open low-rise low density cities in all rings. In contrast, the open low-rise medium density cities had significantly higher SUHI intensity in all rings compared with the compact high density city type and in rings 2 to 4 compared with the open low-rise low density city type. Within the compact high density city type, the proportion of Mediterranean cities was the highest compared with all other city types (89/246 [36·2%]; appendix 1 p 40) and had significantly higher SUHI compared with the green low density cities in rings 1–3 (table 2; figure 3; appendix 1 pp 27–28).

For NO_2, we observed that compact high density and open low-rise medium density cities had significantly higher exposure than green low density and open low-rise low density cities in all rings (table 2; figure 3; appendix 1 pp 29–30). The CO_2 per person emissions were significantly lower among cities within the compact high density type, particularly in rings 0–3. In contrast, the green low density cities had significantly higher CO_2 per person emissions, specifically in rings 0–3 compared with the compact high density cities and in rings 1–2 compared with open low-rise medium density and open low-rise low density cities (table 2; figure 3; appendix 1 pp 29–30). The analyses with alternative data sources for the NO_2 exposure and CO_2 emissions validated these trends (appendix 1 pp 31–36).

In the sensitivity analyses, we observed that the non-Mediterranean cities had an overall higher SUHI than Mediterranean cities in all rings ($p<0·001$; appendix 1 pp 39–40). The exclusion of Mediterranean cities accentuated the differences between the compact high density and green low density cities, in that the compact high density cities had a significantly higher SUHI than green low density cities in rings 0–3 (appendix 1 pp 41–43). In the analysis with the simplified urban extent algorithm, we observed overall lower SUHI estimates compared with the main analysis in all rings (appendix 1 p 45). In this analysis, the green low density type had significantly lower SUHI in rings 1–3 compared with the compact high density cities and in all rings (except ring 1) compared with the open low-rise medium density type (appendix 1 pp 46–49).

Finally, concerning the age-standardised mortality rates, we observed a slightly decreasing trend from the compact high density cities (with an average of 1124 deaths per 100 000 inhabitants) towards the green low density cities (with an average of 1003 deaths per 100 000 inhabitants; table 2; figure 4). Green low density cities had significantly lower mortality rates compared with all other urban configuration types ($p<0·001$; appendix 1 p 50).

Discussion

In this study, we integrated information on intraurban morphological configurations and street design and identified four distinct urban configuration types among European cities. Our findings indicated that compact, higher density cities had increased NO_2 and SUHI effects, along with decreased CO_2 per person emissions. Conversely, greener, lower density cities had lower SUHI intensities, NO_2, and mortality rates, but higher CO_2 per person emissions. The findings of this study hold significant implications for urban and transport planning policies in Europe and contribute to the ongoing discussion regarding which city models can bring the greatest benefits for the environment, climate, and health.

In recent literature,[5] the compact city model has arisen as the optimal theoretical model to promote healthier and more sustainable cities. The combination of destination accessibility, uniform distribution of employment,

Figure 2: **Overview of urban configuration types**
(A) Compact high density urban configuration. An example is shown for the city of Paris, France. (B) Open low-rise medium density urban configuration. An example is shown for the city of Birmingham, UK. (C) Open low-rise low density urban configuration. An example is shown for the city of Gijón, Spain. (D) Green low density urban configuration. An example is shown for the city of Uppsala, Sweden. LCZ=local climate zones.

	Compact high density		Open low-rise medium density		Open low-rise low density		Green low density	
	Mean (SE)	95% CI	Mean (SE)	95% CI	Mean (SE)	95% CI	Mean (SE)	95% CI
Traffic volume (vehicles per day per km)								
City	808 (36)	738–878	495 (18)	460–530	314 (14)	286–342	316 (15)	286–345
Ring 0	930 (82)	768–1093	597 (42)	514–680	397 (37)	324–469	421 (44)	335–508
Ring 1	853 (78)	700–1007	520 (44)	433–607	358 (41)	277–439	345 (37)	273–418
Ring 2	853 (86)	683–1023	454 (33)	388–520	306 (31)	245–366	313 (29)	255–370
Ring 3	748 (84)	582–914	463 (42)	380–545	256 (23)	211–301	255 (28)	199–310
Ring 4	654 (65)	526–782	441 (39)	364–519	253 (25)	203–303	244 (27)	192–296
SUHI (°C)								
City	2·7 (0·1)	2·6–2·9	3·6 (0·1)	3·5–3·7	3·2 (0·1)	3·1–3·3	2·3 (0·1)	2·2–2·5
Ring 0	3·7 (0·2)	3·2–4·1	4·7 (0·2)	4·4–5·0	4·7 (0·2)	4·4–5·0	3·5 (0·2)	3·1–4·0
Ring 1	3·1 (0·2)	2·7–3·5	3·9 (0·1)	3·6–4·2	3·6 (0·1)	3·3–3·9	2·7 (0·2)	2·4–3·1
Ring 2	2·8 (0·2)	2·4–3·1	3·5 (0·1)	3·2–3·8	3·1 (0·1)	2·8–3·3	2·2 (0·2)	1·9–2·5
Ring 3	2·3 (0·2)	2·0–2·7	3·2 (0·1)	3·0–3·5	2·6 (0·1)	2·4–2·8	1·8 (0·1)	1·5–2·1
Ring 4	1·8 (0·1)	1·5–2·1	2·7 (0·1)	2·5–3·0	2·2 (0·1)	2·0–2·4	1·5 (0·1)	1·2–1·8
Tropospheric NO_2 (μmoL/m^2)								
City	59·6 (0·9)	57·9–61·3	59·6 (0·7)	58·1–61·0	50·8 (0·6)	49·6–51·9	52·0 (0·9)	50·3–53·7
Ring 0	61·4 (2·0)	57·4–65·4	61·2 (1·6)	58·0–64·4	52·2 (1·4)	49·5–55·0	53·4 (1·9)	49·6–57·2
Ring 1	60·7 (2·0)	56·8–64·6	60·5 (1·6)	57·3–63·7	51·6 (1·4)	48·9–54·3	52·7 (1·9)	48·9–56·6
Ring 2	59·9 (2·0)	56·1–63·8	59·8 (1·6)	56·6–62·9	50·9 (1·4)	48·2–53·6	52·1 (1·9)	48·3–55·9
Ring 3	59 (1·9)	55·1–62·8	58·8 (1·6)	55·7–62·0	50·2 (1·3)	47·6–52·9	51·4 (1·9)	47·6–55·2
Ring 4	57 (1·9)	53·3–60·8	57·5 (1·6)	54·3–60·6	48·8 (1·3)	46·2–51·4	50·2 (1·9)	46·4–54·1
CO_2 per person emissions (metric tons)								
City	1·3 (0·1)	1·2–1·4	1·4 (0·0)	1·3–1·5	1·7 (0·0)	1·6–1·7	1·9 (0·1)	1·8–2·0
Ring 0	0·5 (0·0)	0·4–0·5	0·8 (0·0)	0·7–0·9	0·9 (0·0)	0·8–1·0	0·9 (0·1)	0·8–1·0
Ring 1	0·9 (0·1)	0·8–1·0	1·3 (0·1)	1·1–1·4	1·6 (0·1)	1·5–1·7	1·9 (0·1)	1·7–2·1
Ring 2	1·3 (0·1)	1·1–1·5	1·5 (0·1)	1·3–1·7	1·9 (0·1)	1·8–2·1	2·5 (0·2)	2·2–2·9
Ring 3	1·9 (0·2)	1·5–2·2	1·7 (0·1)	1·5–1·8	2·0 (0·1)	1·8–2·2	2·4 (0·2)	2·0–2·7
Ring 4	1·9 (0·1)	1·7–2·2	1·8 (0·1)	1·6–2·0	1·8 (0·1)	1·6–2·0	1·9 (0·1)	1·7–2·2
City age-standardised natural-cause mortality rate (per 100 000 inhabitants)	1124 (17)	1091–1157	1093 (14)	1065–1121	1091 (15)	1062–1120	1003 (13)	977–1029

All cities were divided into five rings on the basis of the Burgess concentric urban planning model, with ring 0 being the innermost circle. SUHI=surface urban heat island.

Table 2: **Traffic volume, exposure levels, CO_2 per person emissions, and natural cause mortality by urban configuration type**

management of traffic demand, development of pedestrian and cycling networks, optimum residential density, reduction in distance to public transport, and promotion of active travel modes are all features of compact cities with positive effects for the environment, lifestyle, and social welfare.[5] A set of previous observational studies have shown the environmental and health benefits of compact cities. A study of 53 metropolitan regions in the USA found that the rate of increase in extreme heat events was lower among more compact cities compared with sprawling cities.[41] In addition, a review on urban form and air pollution and a study with 1274 global cities indicated that compactness can result in improved air quality.[42,43] Furthermore, a health impact assessment study of six global cities (Melbourne, Boston, London, São Paulo, New Delhi, and Copenhagen) found that there were health gains when cities transitioned to a more compact urban structure, associated with increases in active travel modes.[44]

However, previous research has also outlined the negative effects of compact cities. Some observational studies have indicated that denser and more compact cities have higher air pollution and UHI intensities, and reduced access to green spaces.[45,46] In addition, highly densified urban environments can contribute to the formation of pollution hotspots, with increased population exposure and health risks.[42,43]

In this analysis, we found that compact cities in Europe tend to have worse air quality, lower green space availability, and increased SUHI compared with lower density cities (table 3). In addition, we observed a decreasing mortality trend from compact to lower density cities, which could be partly linked to the higher adverse environmental exposure among compact cities (appendix 1 pp 51–54).[11,12] Our findings align with previous literature that highlight the adverse effects of compact urban configurations. However, it is important to approach our results with care and refrain from drawing direct conclusions, such as avoiding compact cities, because there are various inter-related factors at play that require further examination and understanding.

Compact cities have many conceptual benefits in terms of reduced car dependency, walkability, proximal access to services, increased social interactions, and an increased sense of community.[5] Yet, in their current configuration, they are highly densified and probably act as economic hubs that attract large numbers of commuters for education or employment opportunities. In addition, mobility within compact cities is still, to a large extent, reliant on motorised transport modes. As revealed by our analysis, traffic volume is considerably higher within the compact city type compared with all other urban configurations, which is also in line with the higher NO_2 observed among these cities. In this sense, current European compact cities should be understood as being in a transition state towards an optimal form, a state that currently combines some positive features (such as proximity to services) with challenges such as densification, mobility, management of traffic flows, poor air quality, and insufficient green and natural spaces.

Several measures can help to optimise compact cities. Regarding density, a medium to high dwelling density ranging from 45 to 175 dwellings per hectare has been suggested as the optimal solution for providing enough density to create an optimal range of services and avoid social isolation and creating a sense of community.[47] However, in cities that are already dense, other measures such as the diversification of local destinations and proximity to public transport might be more relevant.[44] The promotion of active transportation modes is necessary to cover short-distance (generally less than 5 km) mobility needs.[48] Nonetheless, the development of proximal, frequent, and high-quality public transportation is essential to supply the demand for longer distance trips, which still largely rely on private motorised modes, particularly for commuters from suburban areas and nearby towns.[49]

Notably, compact cities can be leveraged for implementing new urban models that promote the creation and better use of public spaces for citizens.[48] These approaches include the implementation of superblocks in various parts of Barcelona, Spain, the development of low-traffic neighbourhoods in London, and the creation of car-free neighbourhoods in Hamburg and Freiburg, with potential positive effects for the environment and health.[48]

In addition, there is a need for strategies to effectively integrate green spaces in compact urban areas.

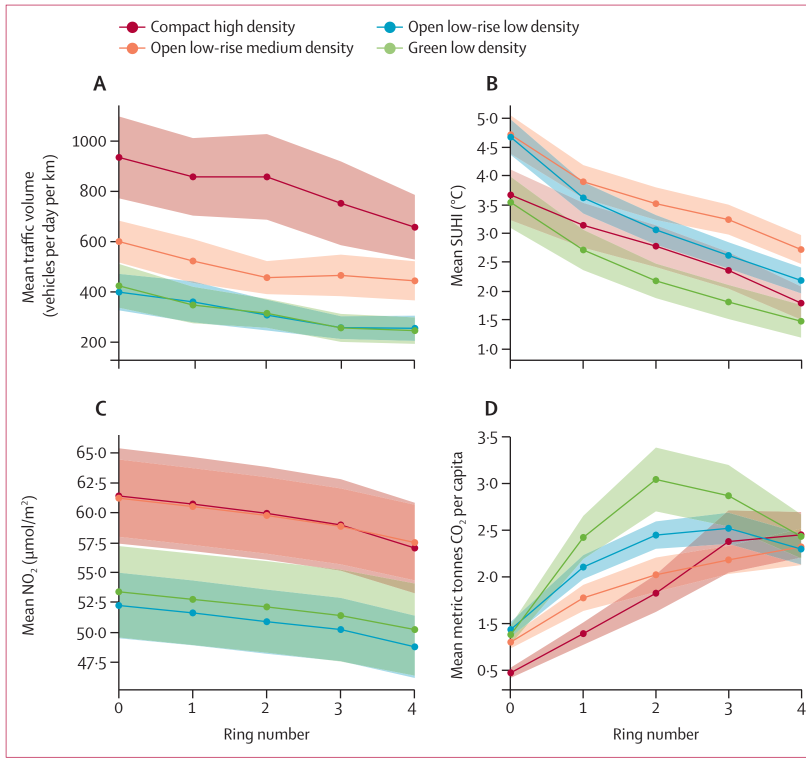


Figure 3: **Motorised traffic flows, SUHI intensity, NO_2 exposure, and CO_2 per person emissions by urban configuration type**
The mean and 95% CIs are shown. SUHI=surface urban heat island.

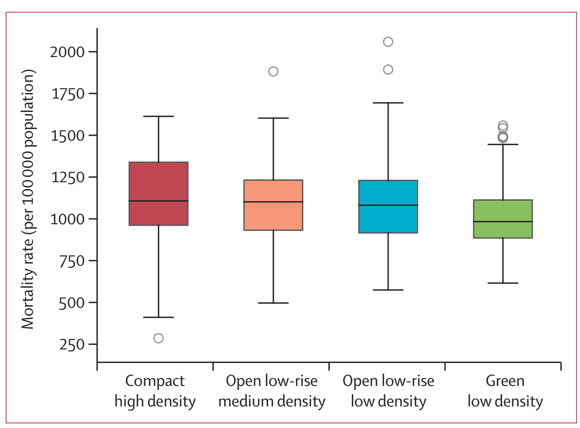


Figure 4: **Age-standardised natural-cause mortality rates by urban configuration type**

Nature-based solutions can take a key role in this regard, not only enhancing green infrastructure, but also mitigating the effects of climate change. A study by Hansen and Pauleit[50] proposed the functional and physical integration of green spaces into the planning of grey infrastructure. Green roofs or façade greening can be introduced in highly sealed commercial areas to reduce surface water runoff.[50] Sky gardens can compensate for the absence of ground-level green spaces; street trees mitigate CO_2 emissions and improve the microclimate;

	Urban configuration					Environmental effect			CO_2 per person, metric tons	Mortality, deaths per 100 000 inhabitants
	Compactness, percentage compact mid-rise	Density, mean population per grid cell	Pedestrian areas, mean m per grid cell	Cycleways, mean m per grid cell	Green space*	Traffic density, vehicles per day per km	NO_2, µmol/m^2	SUHI†, °C		
Compact high density	8·7%	421	33	49	17·3%	808	59·6	3·7	1·3	1124
Open low-rise medium density	2·1%	248	14	38	18·5%	495	59·6	3·8	1·4	1093
Open low-rise low density	1·0%	173	9	22	32·2%	314	50·8	3·5	1·7	1091
Green low density	1·9%	179	15	118	38·5%	316	52·0	3·0	1·9	1003

Mean values by city and cluster are shown. SUHI=surface urban heat island. *Sum of percentage of area of dense trees, scattered trees, and low plants. †Based on the results from the sensitivity analysis excluding Mediterranean cities.

Table 3: **Summary characteristics of the European urban configuration types**

and the introduction of small gardens in public, industrial, educational, and institutional spaces can contribute to supporting biodiversity as part of areas of green spaces in the city.[50] Nevertheless, the increased proximity and availability of urban green spaces might lead to higher property values and the displacement of less affluent residents.[51] Hence, it is crucial for urban planners to monitor the environmental quality, accessibility, and equitable distribution of these spaces among the population to promote environmental and climate justice.

However, our research indicated that compact cities tended to have lower CO_2 per person emissions. This finding is consistent with a previous study involving 53 European cities, which revealed that urban sprawl, characterised by low-density urban fabric and long distances to the city centre, was linked to increased greenhouse gas per person emissions.[52] High urban complexity, irregularity, and fragmentation were identified as key factors contributing to higher carbon emissions, primarily because of the absence of continuity and connectivity in sprawling cities.[53] Because compact cities are denser and offer shorter travel distances, these have the potential to be more energy efficient and allow commuting and carrying out daily activities using low-emitting transport modes. Accordingly, an analysis of 111 Italian cities found that smaller, more compact, and less monocentric cities have reduced levels of CO_2 emissions per commuter, whereas another study in the greater Dublin region, Ireland, estimated that the compact city scenario can lead to reduced household energy consumption and energy-related CO_2 emissions.[54,55] As such, compact cities have the highest harmful environmental exposures compared with all other city types; however, their compactness plays a pivotal role in facilitating low-carbon urban environments.

Lastly, our results highlighted that large and less dense cities are generally greener and perform better in terms of environmental exposures (table 3). However, as mentioned earlier, sprawled cities also face challenges, particularly related to larger travel distances, higher CO_2 emissions, car dependency, availability of proximal and diverse destinations, and social isolation.[5] In these cases, measures such as densification, the provision of services (eg, education, commerce, recreation, and access to jobs), and an adequate mix of buildings with residential and non-residential functions can help in creating more dense and diverse neighbourhoods with cultural, social, and employment opportunities. In addition, not all cities require an equal transformation into a compact form. Although the aforementioned factors might be applicable to new urbanisations or large sprawled and growing cities, they might not be so relevant to small cities with low population densities.

In this study, we discuss some general solutions; however, the development and implementation of the compact city strategies depend on the specific physical, geographical, sociopolitical, economic, and historical aspects of each city. A set of tools and indicators have been developed to ensure more sustainable and healthier urban and transport developments[47,56] and could aid cities to prioritise measures relevant for their local context. Cities need to be understood as complex systems with multiple inter-related dimensions. To address their challenges, comprehensive and integrated solutions are needed that encompass multiple domains including urban and transport planning, housing, education, employment, climate mitigation, and efficient resource use. To achieve this, collaboration among diverse experts in multidisciplinary groups is crucial, as well as the active involvement and commitment of stakeholders through participatory processes.

The main strengths of this study are its innovative analysis, which integrates urban configuration, environmental and climate effects, and health domains; the large number of European cities, high resolution, and the consistency of data; the consideration of spatial variability in all variables; the use of the UMAP algorithm; the incorporation of satellite NO_2 data, which does not depend on any modelling assumptions; and the sensitivity analyses for the definition of SUHI intensity.

Nevertheless, two main limitations need to be addressed. First, we defined European cities on the basis of administrative boundaries, whereas other definitions such as the Morphological Urban Areas definition[57] might provide a more accurate view of urban agglomerations, albeit less linked to policy actions. Second, the data availability and definition of detailed indicators were limited for many European cities. For instance, because of inconsistencies in the OSM database, we could not include the connectivity of the general road network or the pedestrian and cycling networks. Similarly, we could not reflect the accessibility to public transportation, natural areas, or services such as food markets or convenience stores. However, these indicators have been proven to be relevant for sustainability and health, and should be considered in future studies.[58]

Furthermore, several methodological considerations exist. First, there are multiple methods for estimating the SUHI that, as shown in our analysis, can lead to considerable variability in the results. In this study, we estimated the SUHI as the LST difference between urban and rural areas surrounding each city boundary. Although this is the most accepted method for SUHI estimation, it can also lead to misleading interpretations depending on climatic regions, biome, abundance and diversity of vegetation, irrigation patterns, and droughts, particularly for semi-arid cities.[38] Given this issue, we conducted a sensitivity analysis with an alternative SUHI definition that takes the non-urban areas within each city boundary as the LST reference. This definition eliminates the influence of extrinsic factors that might affect rural LST. However, given that this definition takes green urban areas as a reference to calculate SUHI, which is artificially originated, it is limited in providing an accurate measure of the excess heat resulting from the anthropogenic modification of natural landscapes and, accordingly, results in lower SUHI estimates. Additionally, differences between UHI and SUHI need to be acknowledged. In this study, the SUHI proxy was used because of limited UHI data availability for many European cities. However, the association between the SUHI and UHI might vary according to other factors (ie, elevation and terrain roughness) in a non-linear manner.[59,60]

Second, we worked with the best available NO_2 dataset derived from satellite observations without any chemical transport modelling. However, it should be noted that satellite-derived NO_2 does not directly represent pollutant concentrations at the ground level. Despite this, it has been shown to constitute a good proxy and a reliable tracer of anthropogenic emissions,[25] which was further supported by our validation analysis using monitoring stations (appendix 1 pp 35–36).

Finally, it is crucial to acknowledge that the mortality association is based on an ecological analysis and might be influenced by various unaccounted factors, such as socioeconomic conditions, population behaviours, habits, and health-care provision. However, it was the best available indicator for most cities examined in this study. Furthermore, this analysis represents one of the initial broad examinations of the connection between urban configuration and health in Europe. Notably, there is a small body of research in Latin America, with only a few studies globally and in Europe.[30–33] One 2019 study across Europe aligns with our findings, showing a reduction in mortality in cities characterised by natural green spaces.[33] This underscores the need of additional epidemiological studies to deepen the understanding of the intricate relationship between urban configuration and health outcomes.

In conclusion, we identified four distinct European urban configuration types and evaluated their association with motorised traffic flows, SUHI, NO_2 emissions, CO_2 emissions, and natural-cause mortality rates. Our findings suggest that, although the compact city model has arisen as the way forward to healthier and more sustainable cities, present day European compact cities should be understood as being in a transition state that combines positive features, such as access to services and reduced carbon emissions, with challenges such as high traffic volumes and a poor environmental quality. Cities are complex systems and solutions require a holistic approach. A set of policy measures has been proposed to promote more sustainable and healthier urban and transport developments. These measures need to be evaluated at the local level and actions relevant for each city's local context need to be prioritised.

Contributors

TI, SK, and MN conceptualised the study idea. TI and SK worked on the study design. MC worked on data collection. TI and SK did the data analysis. TI, SK, EPB, MC, KG, PP, TE, HT, and MN contributed to data interpretation. KG and PP provided input on the Uniform Manifold Approximation and Projection for Dimension Reduction and clustering. TE and HT provided the NO_2 data. TC calculated the surface urban heat island intensity using the alternative estimation method. TI and SK wrote the manuscript. TI, SK, EPB, and MC accessed and verified the data. All authors reviewed the manuscript and provided feedback on the study design, data analysis, and interpretation of results. All authors were responsible for the decision to submit the manuscript for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All data collected are routinely collected generally aggregated data without the possibility of identifying specific people. All data are available upon request to the corresponding author (mark.nieuwenhuijsen@isglobal.org) and with the agreement of the steering group. Map data copyrighted OpenStreetMap contributors are available from https://www.openstreetmap.org. The Sentinel-5P and TROPOMI data are provided via the Copernicus Open Access Hub (https://s5phub.copernicus.eu/).

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