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Decoupling density from tallness in analysing the life cycle greenhouse gas emissions of cities

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The UN estimate 2.5 billion new urban residents by 2050, thus further increasing global greenhouse gases (GHG) emissions and energy demand, and the environmental impacts caused by the built environment. Achieving optimal use of space and maximal efficiency in buildings is therefore fundamental for sustainable urbanisation. There is a growing belief that building taller and denser is better. However, urban environmental design often neglects life cycle GHG emissions. Here we offer a method that decouples density and tallness in urban environments and allows each to be analysed individually. We test this method on case studies of real neighbourhoods and show that taller urban environments significantly increase life cycle GHG emissions (+154%) and low-density urban environments significantly increase land use (+142%). However, increasing urban density without increasing urban height reduces life cycle GHG emissions while maximising the population capacity. These results contend the claim that building taller is the most efficient way to meet growing demand for urban space and instead show that denser urban environments do not significantly increase life cycle GHG emissions and require less land.

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INTRODUCTION

Population and urbanisation are increasing with an estimated additional 2.5 billion people living in urban areas by 2050¹. The built environment is the greatest cause of carbon emissions, global energy demand, resource consumption and waste generation². In the European Union (EU), it accounts for 50% of all extracted materials, 42% of the final energy consumption, 35% of greenhouse gases (GHG) emissions and 32% of waste flows³. Therefore, achieving optimal use of space and maximal efficiency in buildings is fundamental for the transition to sustainable built environments and to progress towards national and international climate targets.

The design of urban environments has not rigorously considered life cycle GHG emissions (LCGE hereon), focusing instead on reducing the operational energy demand and the carbon emissions associated with the energy used to operate buildings. Operational energy use occurs while the building is in service, and includes heating and cooling, lighting, and other plug loads. The use of operational energy contributes to the LCGE of a system as the energy grid is not carbon free, thus conversion factors can be applied to convert between units of energy used and carbon dioxide equivalent (CO_{2e}), the metric of LCGE. LCGE includes these operational emissions as well as the embodied emissions of the entire system. Embodied energy and CO_{2e} emissions are the hidden, “behind-the-scenes” energy and emissions that are used or generated during the extraction and production of raw materials, the manufacture of the building components, the construction and deconstruction of the building, and the transportation between each phase⁴. As operational efficiency grows, so does the share of embodied impacts on the whole-life balance, thus reinforcing the need for sustainability analyses of buildings and cities to be underpinned by a life-cycle-based approach^{5,6}. In other words, operational energy and carbon savings should not be made at the expense of the embodied

impacts, and a holistic approach focused on reducing LCGE should be the primary aim.

Apart from a few studies focusing on urban morphology and energy demand^{7,8} in the built environment, there has been a growing belief that building taller and denser is better, under the idea that tall buildings make optimal use of space⁹, reduce operational energy use and energy for transportation^{10,11}, and enable more people to be accommodated per square metre of land¹². However, this is only partly true. As buildings grow taller they need to be built further apart; for structural reasons, urban policies and regulations, and to preserve reasonable standards of daylight, privacy and natural ventilation¹³. Furthermore, for a fixed amount of internal volume (e.g. expressed in terms of floor area times the inter-storey height) an increase in the building's tallness corresponds to an increase of the building slenderness and hence to a reduction of its compactness which is detrimental to space optimality¹⁴. Urban density is commonly defined as the ratio of built land area (i.e. building footprints) to total land area yet this metric does not capture building height.

Height has been captured in urban density metrics by summing the total floor space of an urban environment and dividing by the total land area¹⁵. To date, however, no method exists to (i) analyse density and tallness of urban environments independently of each other or (ii) evaluate their influence on the LCGE of urban environments. These are the two main objectives of this paper. To decouple the two (i.e. density and height) we propose an additional metric for describing urban environments through a ‘tallness’ factor, or the average height of an urban area. This informs a method that includes a model to generate synthetic, yet realistic, parametric urban environments based on a number of input variables, as detailed in the Methods section. To embed such realism, we collected primary data on real urban environments since building regulations vary greatly across any one country, due to the devolved powers of local authorities in matters of urban planning. Therefore, picking any single value for building

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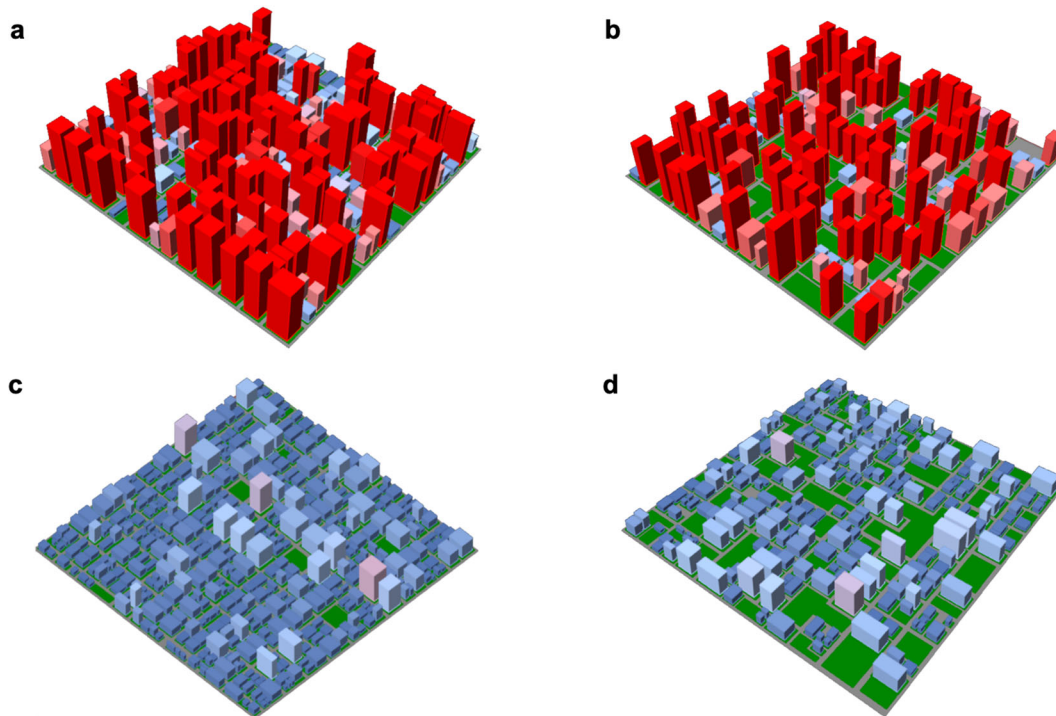


Fig. 1 Illustration of the different of urban typologies classified in the present analysis. **a** HDHR, **b** LDHR, **c** HDLR, **d** LDLR. The height of each building is mapped to the colour with blue as low heights and red as high heights.

footprint, sizes, number of storeys, distance with adjacent buildings, etc. could bias our results. As an alternative, we surveyed 25 addresses in the UK (in the cities of London, Edinburgh, Glasgow, Manchester, Leeds, Sheffield and Birmingham) to measure these key building characteristics and neighbourhood constraints. The choice of the addresses we surveyed was due to proximity to the authors to ensure a good coverage of the key inputs to our analysis and the possibility of site visits where needed. In the attempt to avoid a sole UK focus of our study, we verified these primary collected data against spot checks in the European cities of Berlin, Oslo, Stockholm and Vienna, obtaining good agreement.

For each of the 25 addresses we surveyed, we extended our analysis to 1 km², with each building at the centre, and collected the following data: number of blocks, number of green spaces, average block perimeter, average block area, average green space perimeter, average green space area, average street width, average main road width, average distance to surrounding buildings, and width and depth of the building plot (including gardens, driveways, etc.). These inputs ensure the synthetic urban environments stem from real-world observations. For each urban environment we assess, at the building level, both embodied and operational emissions to inform a whole-life set of results. While our model and method are applicable irrespective of the geographical context of analysis, the results of their application—while aimed at a broad European context—remain rooted in UK primary data. The results for such context are shown in the next section.

RESULTS

Density and tallness of urban spaces

Urban environments are diverse, arguably unique, and the product of many factors such as the landscape, culture, economy and history. Yet, a common theme throughout urban environments is the types of buildings that comprise them. These can be categorised as non-domestic low-rise (NDLR); non-domestic

high-rise (NDHR); domestic low-rise (DLR); domestic high-rise (DHR); and terraced or semi-detached houses (House)^{16,17}. Full details are given in the Supplementary Information (specifically Supplementary Methods 1, Supplementary Table 1 and Supplementary Methods 3). The layout and combination of these different building types contribute to both the density and height of an urban space^{13,18–20}.

In this study, we offer a LCGE analysis of urban environments by decoupling and analysing both tallness and density. Through our method, we parametrically simulate 5000 urban environments under two scenarios and perform a cradle-to-grave process-based life cycle assessment on each to evaluate the LCGE. Scenario 1 considers fixed populations of 20, 30, 40 and 50 thousand people with varying land area, while Scenario 2 considers a fixed land area of 1 km² with varying populations potentially supported. We compare the LCGE of each urban environment to evaluate if taller and denser environments yield greater efficiency in terms of accommodated population, land use, energy demand and GHG emissions. This multi-criteria approach provides a more holistic picture of the LCGE of urban environments and can inform better policies and practice related to urban design and planning.

While a large variety of urban typologies could be defined with respect to density and height, we define four typologies for discussion herein: high density, high-rise (HDHR); low density, high-rise (LDHR); high density, low-rise (HDLR); and low density, low-rise (LDLR). Examples of these urban environments are visualised in Fig. 1. An area of midtown Manhattan in New York City, USA, is an example of a HDHR urban typology with a density factor of approximately 54.5 and a tallness factor of 54.2. Central Paris is an example of a HDLR urban typology with a maximum density factor of 62.6 and tallness factor of 7.5. LDLR urban typologies are commonplace in suburban metropolitan areas, or urban “sprawl,” while LDHR environments have been envisioned by many urban planners, notably by Le Corbusier’s design of the “Radiant City”²¹. Details around the determination of the cut-offs for each urban typology (Supplementary Discussion and Supplementary Methods 1) as well as the procedural flowchart of the

algorithm behind our model are given in the Supplementary Information (Supplementary Methods 2).

For each of the five types of building considered herein, the LCGE results are presented in Table 1, separated by life cycle stage as defined by BS EN 15978:2011⁴. As expected, the structural system of each building contributes significantly to the cradle-to-gate emissions. With a 60-year lifespan assumed for all buildings²², the operational impacts represent between 77–83% of the LCGE. Non-domestic buildings typically have higher LCGE than domestic buildings, while high-rise buildings have greater LCGE than low-rise buildings which is consistent with findings from other studies^{5,23,24}. These LCGE results for different building types feed into the 5000 parametrically simulated urban environments which are explored under the two previously defined scenarios.

Scenario 1: fixed population

Figure 2a illustrates the LCGE of all simulated urban environments for the four population scenarios: 20, 30, 40 and 50 thousand people, while Table 2 shows key results for LCGE and land area (averages and standard deviations) for each population cluster. Across all four populations, the LCGE increases as tallness increases, independent of the amount of land required to house the population. In contrast, the density of buildings has little impact on LCGE; for each population, low- and high-density typologies result in similar LCGE results. If the simulated environments are separated into their height-density typologies, we find that between the LDLR and HDLR typologies, there is a decrease in the average LCGE as population increases: 10% decrease for a 20k population, 16% for 30k, 19% for 40k and 15% for 50k. A key difference between LDLR and HDLR typologies is the built land area required to accommodate the same number of people. HDLR typologies require 49–56% less land than LDLR, resulting in lower LCGE impacts and less demand for land. Percentages in the discussion of the results always refer to comparison across the averages reported in Tables 2 and 3.

High-rise buildings have much higher LCGE than low-rise buildings, as shown by the large bubbles in Fig. 2. Thus, building taller has a significant impact on the LCGE of an urban environment when the number of people is kept constant. For a 20k population, moving from a HDLR (small purple bubbles) to a HDHR (large purple bubbles) typology results in a 140% increase in LCGE; for 30k, 40k and 50k populations, the difference is 154, 143 and 132%, respectively. Compared with the difference between LDLR and HDLR typologies presented above, this shows the much greater impact of building taller over building denser.

From Table 2 it is possible to see that, for all the fixed populations, HDLR buildings minimise LCGE. HDHR is the worst-case scenario for all populations, ranging from a 27 to 77% increase in LCGE when moving from a 20k to a 30k and 50k population, respectively. However, the impact on LCGE with increasing populations is higher for the other urban typologies, despite absolute LCGE being much higher. For a LDLR scenario, doubling the population, i.e. from 20k to 40k, results in an 81% increase in LCGE; moving from 20k to 50k gives a 94% increase. In terms of increasing impacts with greater populations, LDHR shows the highest differences; 112% LCGE increase moving from 20k to 40k and 145% moving from 20k to 50k. This suggests that the land required, and thus the land use change emissions factor, to accommodate higher populations plays a role in LCGE. This is reflected in the larger land areas required when building low-density typologies for higher populations; in a LDHR scenario, moving from 20k to 30k results in a 53% increase in land area and from 30k to 40k and 50k populations, the difference is 115 and 152%, respectively. However, the small absolute LCGE increase does not reflect the large increase in land required suggesting the relatively insignificant impact land use change has on LCGE.

Table 1. Embodied carbon coefficients (ECC) and operational carbon coefficients (OCC) used to determine a LCGE coefficient for each building type, normalised per square metre of floor area.

	ECC (A1–A3 Structure) ²⁵ kgCO ₂ e m ⁻² FA	ECC (A1–A3 Façade) ²⁶ kgCO ₂ e m ⁻² EA	ECC (A1–A3 Roof) ²⁷ kgCO ₂ e m ⁻² BF	ECC (Stage A4) ⁶ kgCO ₂ t ⁻¹ km ⁻¹	ECC (Stage A5&C) ⁶ kgCO ₂ e m ⁻² FA	OCC (over 60 years) ^a kgCO ₂ e m ⁻² FA	LCGE kgCO ₂ e m ⁻² FA
Non-domestic low-rise	180	72	21	0.19	221	2460	2953
Non-domestic high-rise	250	168	21	0.19	221	2460	3120
Domestic low-rise	180	76	33	0.19	221	1898	2426
Domestic high-rise	250	61	33	0.19	221	1898	2462
Terraced/house	90	84	36	0.19	221	1491	1925

^aDerived from operational energy estimates for non-domestic buildings²⁸ and domestic buildings²⁹. Units are given below each element considered: structure, façade and roof ECCs all refer to Stage A1–A3 (i.e. from raw material extraction to manufacturing generally referred to as cradle-to-gate). A4 refers to transportation to site and A5 to construction activities in line with the EN 15978 terminology on a building's life cycle stages. FA floor area, EA envelope area, BF building footprint.

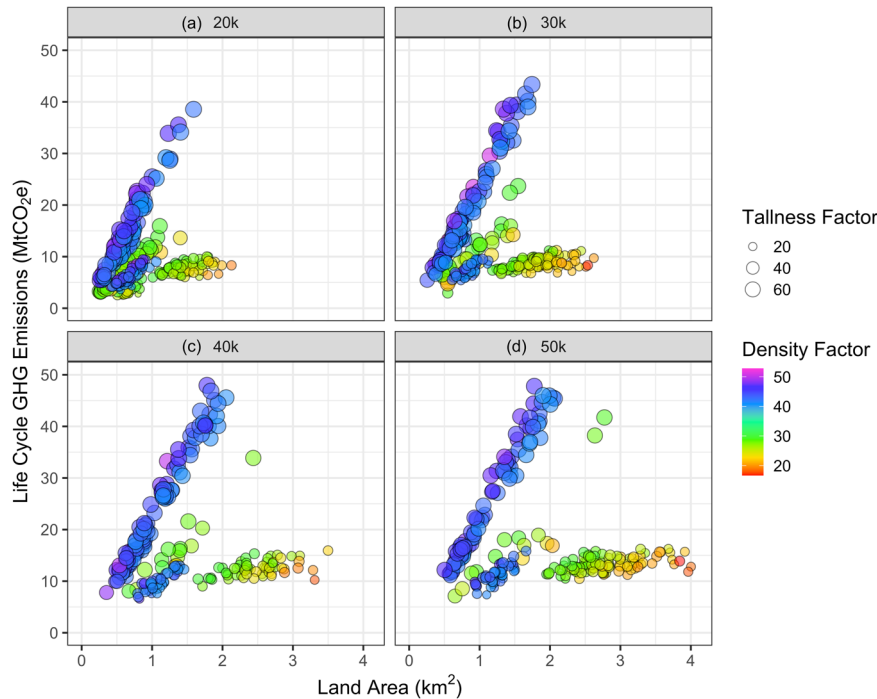


Fig. 2 LCGE versus built land area for fixed populations. Results presented for 20 (a), 30 (b), 40 (c), and 50 (d) thousand people.

		LDLR		LDHR		HDLR		HDHR	
		Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
20k	LCGE (MtCO ₂ e)	6.82	2.08	7.44	3.46	6.12	1.52	14.68	7.07
	Land area (km ²)	1.32	0.41	0.62	0.29	0.67	0.14	0.65	0.26
30k	LCGE (MtCO ₂ e)	8.69	1.21	11.20	4.75	7.32	1.18	18.60	9.79
	Land area (km ²)	1.82	0.34	0.95	0.35	0.84	0.12	0.81	0.36
40k	LCGE (MtCO ₂ e)	12.37	1.49	15.8	6.20	9.98	1.83	24.25	10.88
	Land area (km ²)	2.48	0.41	1.33	0.42	1.11	0.19	1.07	0.44
50k	LCGE (MtCO ₂ e)	13.2	1.38	18.2	9.94	11.2	1.83	26.01	11.4
	Land area (km ²)	2.81	0.49	1.56	0.65	1.24	0.17	1.16	0.46

The distribution of building types across the four population models is shown in Fig. 3. For the higher populations (40k and 50k), proportionally more domestic buildings are selected in order to accommodate the need for more residences. This need is particularly illustrated through the 50k population model in which domestic low-rise buildings dominate any other building type across all simulations.

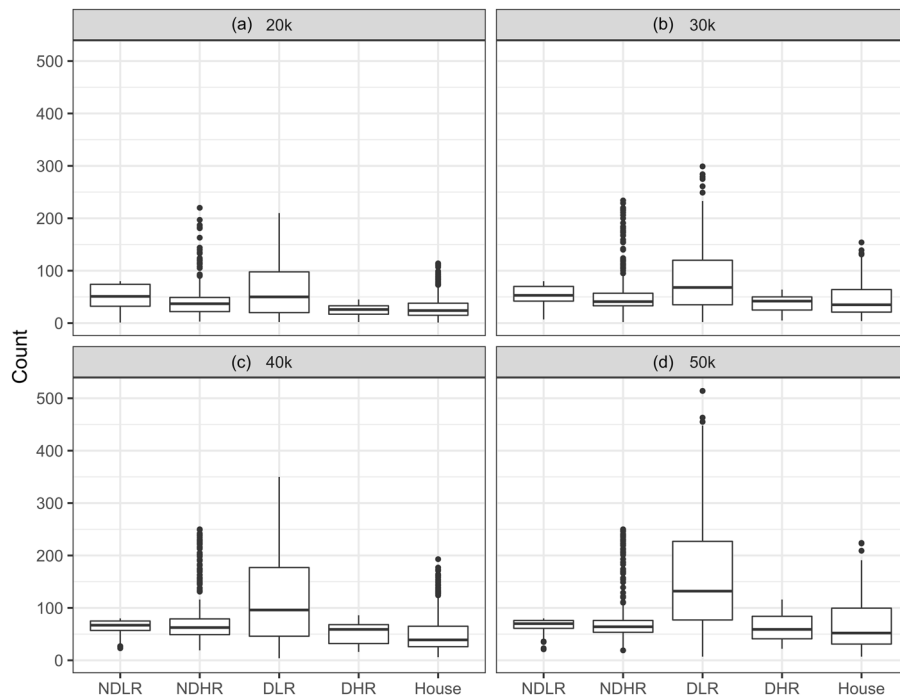
When LCGE is normalised per building type, non-domestic buildings have the highest share of the impact at 75% (62% for non-domestic high-rise and 13% for non-domestic low-rise), so their inclusion in the urban scenario inherently increases LCGE. Domestic buildings account for the remaining 25% with the following split: 17% for domestic high-rise and 4% for both domestic low-rise and terraced/house. This split in LCGE impact aligns with the results presented in Table 1. As expected, non-domestic buildings are responsible for the largest portion of LCGE due to having higher operational emission intensities. This value will become less significant as a driver for higher non-domestic impact in future years due to the decarbonisation of the grid and reduced reliance on fossil fuels²⁵. Therefore, the next hotspot to address from a LCGE perspective is the structural system of buildings, which is largest in high-rise buildings, both domestic

and non-domestic. Beyond that, the largest difference is seen in the façade; non-domestic high-rise buildings have at least twice the impact of the other four building types, due to the heavy material intensity of steel and glass^{26,27}.

In terms of land area, the difference between LDHR and HDHR urban typologies is not as stark as the low-rise scenarios. The LDHR scenario requires between 17–34% more land for a 30k population and 50k population, respectively. Essentially, more people require more space, but high-rise buildings require a similar land area compared to low-rise buildings with varying density. This is due to the space required when building taller; buildings must be further apart for structural reasons, urban policies and occupant comfort. Therefore, building taller to accommodate a growing population not only does not save space but also significantly increases LCGE. A note here might be on whether the additional empty space between high-rise buildings is transformed into urban greenery that can sequester carbon. Evidence in support of this can be found in the work of Zirkle and colleagues²⁸, who modelled carbon sequestration in home lawns in the US finding a technical sequestration potential ranging from 25.4 to 204.3 g C m⁻² year⁻¹. Their work covers different US zones with their own climates, ranging from cases

Table 3. Summary of the LCGE and population accommodated with a fixed land area for the four urban typologies.

	LDLR		LDHR		HDLR		HDHR	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
LCGE (MtCO ₂ e)	7.11	0.60	15.10	3.02	8.79	1.16	24.98	2.69
Population (thousands)	21.04	5.19	42.69	12.70	46.66	12.65	57.80	18.98
LCGE per capita	0.34	0.12	0.35	0.24	0.19	0.09	0.43	0.14

**Fig. 3** Count of building types for each simulated urban environment across the four population models. Results presented for 20 (a), 30 (b), 40 (c) and 50 (d) thousand people. Quantitative comparison between the typologies in our synthetic environments and those observed in real urban environments—showing good agreement—is offered in the SI (Supplementary Fig. 3).

(arid southwest) where the lawn management (energy, irrigation, fertilisers, etc.) can offset the net carbon sequestration to others (northeast) where best practices for lawn management show a significant and promising net carbon sequestration potential. We are therefore unable to immediately translate such values into inputs to our model to capture carbon sequestration of urban greenery, but this undoubtedly is an important point for future work.

Figure 4 presents the LCGE as a function of the tallness and density factor for each fixed population. This visual representation shows that LCGE increases with increasing height and that high-rise buildings are more commonly paired with high density typologies. Furthermore, this representation illustrates that the LCGE of different densities is less stratified than for building height, reinforcing the finding that building height has a significant impact on LCGE, while density does not.

Scenario 2: fixed land area

Figure 5 illustrates the LCGE for different combinations of density and height for a fixed land area of 1 km². This plot is more variable and does not show the same trends that were identified in Fig. 2. There is a pattern whereby LDLR (small red bubbles) exhibit the lowest LCGE and HDHR (large purple bubbles) have the highest. Therefore, in this scenario, LDLR is the best-case in terms of minimising LCGE and HDHR is the worst. However, LDHR can

accommodate 103% more people than a LDLR scenario and HDLR and HDHR scenarios can accommodate 122–175% more, respectively. On average, more than twice as many people can be accommodated in a HDLR scenario for a similar LCGE, with 21k people at 7.11 MtCO₂e for LDLR and 47k people at 8.79 MtCO₂e for HDLR. Thus, HDLR would offer a better solution; invest 24% more carbon to accommodate 122% more people. With high-rise scenarios, LCGE significantly increases compared to LDLR; 112 and 251% more LCGE in LDHR and HDHR scenarios, respectively. Therefore, the carbon investment does not seem justified. Changing the density from low to high has little impact on the LCGE in low-rise scenarios, as shown in Table 3. However, moving to high-rise structures results in a significant impact on LCGE with a 184% increase moving from HDLR to HDHR.

DISCUSSION

With an aim to evaluate the widespread belief that building dense and tall is the only way to accommodate a growing urban population, we developed and employed a method to separate density from tallness in urban environments and establish the extent to which each influences the LCGE of cities. Indeed, the difference between varying urban scenarios and across varying populations had yet to be quantified from a LCGE perspective. We found that while tallness does significantly increase the LCGE, density does not, and we here suggest that there is an alternative

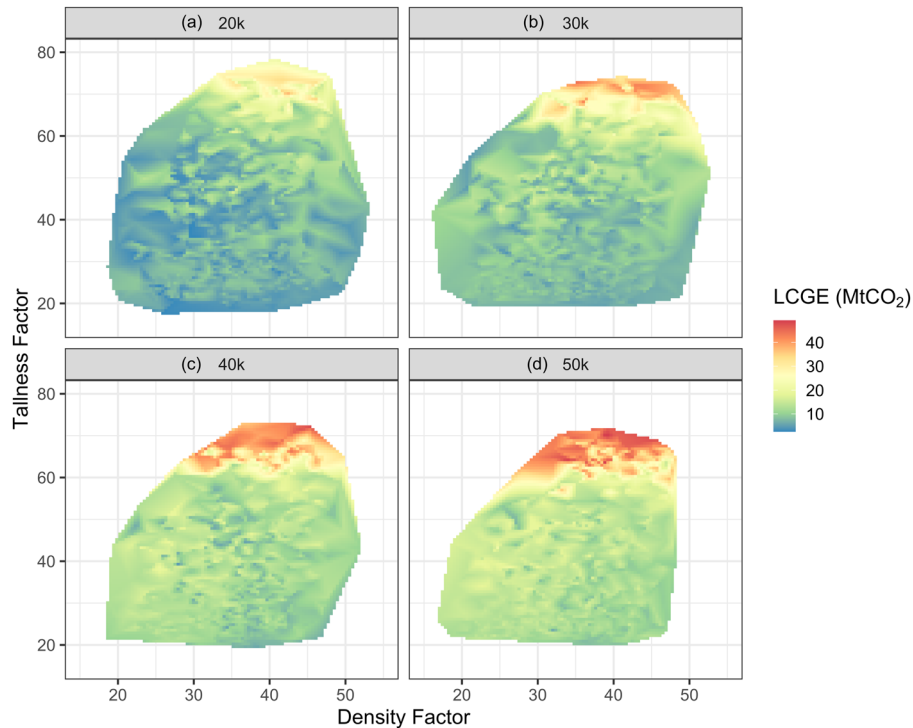


Fig. 4 Colour maps for the fixed population conditions under investigation. Results presented for 20 (a), 30 (b), 40 (c), and 50 (d) thousand people. A spline interpolation is used to interpolate between each simulated urban environment.

low-rise pathway for urban development that can meet the growing demand for urban floor area. While not explored in detail, it is worth considering that low-rise urban environments also allow to choose from more construction materials than the handful of elite materials that govern and dominate our high-rise built environments (i.e. steel, reinforced concrete, aluminium and glass).

Specifically, in terms of LCGE impacts, HDLR urban typologies are the best-case scenario for a fixed population. This can even be argued to be the case for a fixed land area, despite a higher absolute LCGE output than the LDLR typology, due to the much greater number of people that can be accommodated. For the case of fixed populations, it may be surprising that LDLR typologies do not have the lowest impact. However, due to the larger land areas required to accommodate the same population, the land use change factor pushed the impact past that of HDLR though there is only a relatively small difference between them (10–19%). Given the growing pressure and competing demands on land as a resource it is however only reasonable to assume it is used as efficiently as possible, and this is what HDLR urban typologies do. The worst-case scenario for a fixed land area is the HDHR typology, as population does not constrain the number of buildings or type that can fit within the 1 km² boundary. For the fixed population conditions, the worst-case scenario is also HDHR (followed by LDHR) suggesting that there seems to be no supporting evidence behind the necessity for high-rise urban environments.

While simulation based, our synesthetic urban environments (i) stem from primary data collected in real-world neighbourhoods (Supplementary Methods 2 and 3 and Supplementary Note) and (ii) match well with the features revealed by analysis of today's cities (Supplementary Method 1 and Supplementary Fig. 3). As such they can effectively support both better urban policies and more environmentally sustainable urban design and planning. For instance, when new mixed-use neighbourhoods are being developed or redeveloped, our method and model can offer important insights to inform policies in order to meet the desired

targets (e.g., population to be housed and/or non-domestic floor area to be achieved) while reducing LCGE. Similarly, in parts of the world where new cities are being built from scratch (e.g. China) or where this could happen in the near future (e.g. Africa) our research could support urban planning and design. Significantly, the EU/UK geographical context of our work only affects the underlying data and not the model and method which could feed off machine-readable data representative of any country in the world.

Future potential applications of the model and method could investigate 'optimal' values for urban density and tallness given specific constraints or support the development of a dynamic modelling element that interacts with the analysis of density and tallness. In addition, the results of this study suggest that there is no merit to the claim that building denser and taller is more sustainable. By building dense, low-rise urban environments, the same populations can be accommodated for drastically lower carbon costs and without having to significantly increase land use.

Limitations and recommendations

The model limitations are covered in detail in the accompanying Methods section. To capture the stochastic nature of urban areas, a simulation-based methodology is used. A limitation of this approach is that the model selects building types based on the plot size and desired height. Although we checked that, overall, our share of domestic vs. non-domestic building types match that of real urban environments, a fully simulation-based approach could present simulation bias. Further, while we based our input variables selection on extensive data collection of real urban environments (e.g. distance between neighbouring buildings), these input variables could all be subjected to sensitivity analysis to further unravel the extent of the role they play in determining the LCGE of urban environments. An element where this would become particularly useful is to adopt a continuous distribution of buildings' heights to choose from. This would remove the simplification between low-rise and high-rise that we introduce in this research to be able to

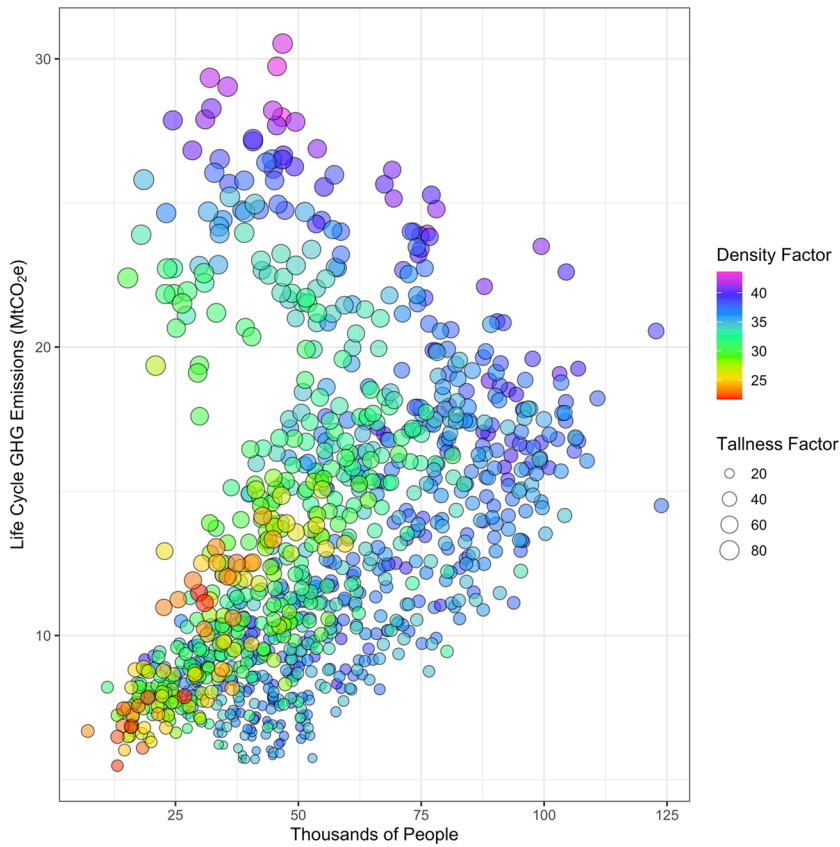


Fig. 5 Density, tallness, and life cycle GHG emissions. LCGE versus number of people accommodated for a fixed land area.

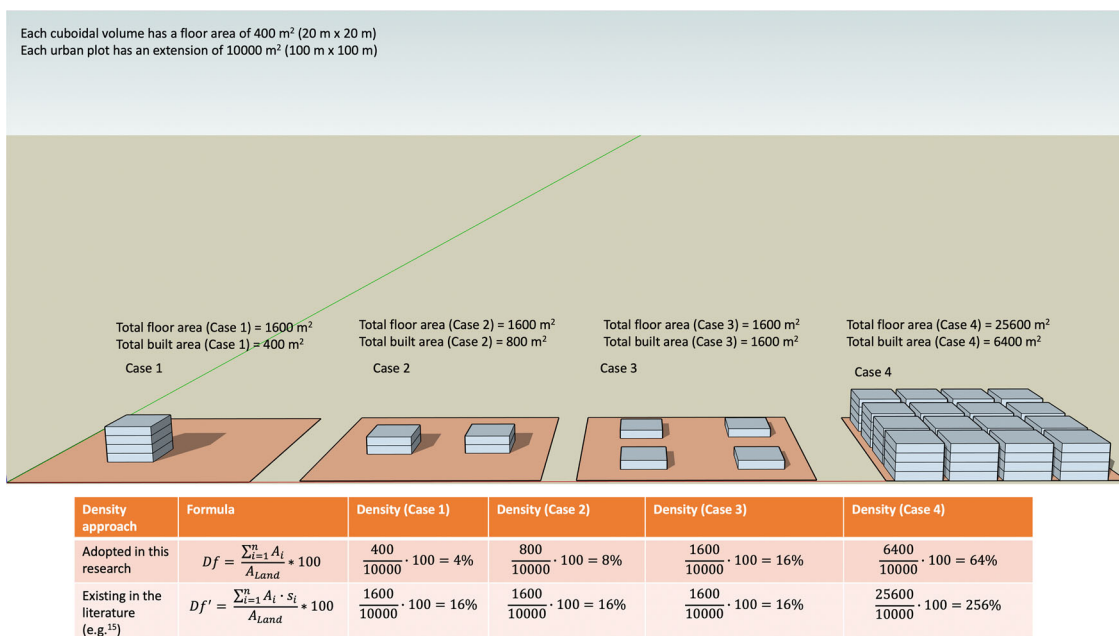


Fig. 6 Metrics of urban density. Comparison between floor-area-based metric of urban density and land-occupation based metric (adopted by the authors).

compare the two. Furthermore, to aggregate the embodied GHG emissions values for the substructure and roof, generalisations were made based on average values obtained from literature. Additionally, for land use, land-use change and forestry (LULUCF) we adopt

conventionally agreed factors from the leading database ecoinvent. The land use change method adopted and the assumptions of the previous use of land also warrants further research to increase the understanding of the importance of this variable.

These limiting assumptions were necessary based upon the urban scale scope of this study. Providing additional levels of detail at the building scale would greatly improve the accuracy of the analysis and can be refined in future works. Employing a cradle-to-cradle approach to consider resource reuse, the impact of retrofitting existing building stock over rebuilding; the inclusion of transportation impacts; adding a dynamic time component to investigate material inflows and outflows; and including a detailed time-related analysis of carbon sequestration potential offered by urban greeneries in the simulated environments—are all valuable and important avenues for future work to build on this study and expand its relevance while reducing its limitations. This study therefore acts as a stepping-stone to provide a strong foundation from which extensive future work can be born.

When considering LCGE, which encompasses both embodied and operational GHG emissions, the results provide further insight to dispel the growing belief that taller and denser is better. These findings support the growing claim to resolve the unnecessary opposition between embodied versus operational and re-unite them both into the physical unity of a built asset. For example, it has been argued that the environmental impact of the operational phase of cities can be alleviated by green plant coverage, i.e. vegetation façades²⁹. However, to support such an additional load there needs to be more materials in the building structure thus increasing the embodied impact. Additionally, vegetation covering the façade may offset carbon emissions, but it also shades the entire façade increasing the need for mechanical means of ventilation, daylighting and heating.

Sustainability is a three-legged stool comprising the economy, the environment and society: to be truly sustainable all three must be in equilibrium. Therefore, interdisciplinary considerations that need to be addressed when progressing this work include, for instance: occupant comfort; the urban heat island effect; competing land use; the carbon sequestration effect of green spaces; urban policies; resource consumption; how the urban environment affects crime; etc. Cities are the central hub of modern society and to address these multi-faceted issues a highly multidisciplinary approach seems the only appropriate way forward.

METHODS

Life cycle assessment methodology

To determine LCGE, carbon coefficients for the different life cycle stages and building components were found from existing literature. Table 1 outlines these results and the embodied and operational carbon coefficients for the five building types considered. A cradle-to-grave life cycle assessment was conducted for this study, accounting for the 100-year global warming potential (GWP100) measured in kilograms of carbon dioxide equivalent (kgCO_{2e}). Here, carbon impact and LCGE are used as shorthand for GWP100. Resource reuse or recycling was excluded since it is beyond the scope of the study. With respect to building components, the core structure, building façade and roof were included while the foundations for all building types were excluded. The lifespan for each building type was assumed to be 60 years, after which the buildings are assumed to be demolished and materials sent to landfill. To accommodate for a decarbonising energy mix, a steady decarbonisation rate of 6.4% per year was applied as this is the rate required to limit global warming to 2°C ³⁰. For the models with fixed populations, a land use change factor, 0.08 kgCO_{2e} per m^2 , was added to account for the changing land area. This factor was taken fromecoinvent³¹ and is specific to construction processes. The focus of this analysis is limited to a UK and European context to reflect the regional variations of lifecycle inventories, which are highly dependent upon the region in which the data is collected³².

Twenty-five case studies were used to generate primary data on the building parameters which were utilised as inputs to the parametric model. Buildings in the UK were chosen to collect primary data due to physical proximity and possibility of accurate measurements and site visits when needed. These collected data were then used to cross-check other buildings in Berlin, Oslo, Stockholm and Vienna to make our analysis

relevant to the broader Europe (full details in Supplementary Methods 1 and Supplementary Note). To determine the LCGE of the built forms, in kgCO_{2e} per m^2 , embodied carbon coefficients (ECCs) for different construction materials and the different life cycle stages were found from existing research and emissions databases^{5,31,33–35}. These values were then multiplied by the normalised material intensities found during primary data collection to arrive at the LCGE impact of each building type. Full details are available in Supplementary Methods 3.

The embodied carbon of the façade was calculated from the envelope area and the roof from the building footprint; the ECC of each buildings' structure was taken directly from the literature³⁶. The life cycle was considered from Stages A–C, cradle-to-grave, and the operational carbon coefficients were derived from operational energy estimates provided by DECC and DBEIS^{37,38}.

Parametric model

A bespoke parametric model was developed for this work that allowed the density and height of building plots to be stochastically selected from predefined ranges (Supplementary Methods 2). The ranges were informed by the case studies for the five building types considered in this work. The benefit of this randomisation lies in the variety of realistic built forms that can be developed, computed and assessed. Likewise, block size and street sizes were captured from the case studies. Existing buildings in urban environments were surveyed and data were collected for a number of building characteristics (e.g. population density, storey height, perimeter, building footprint, etc.) and neighbouring constraints (e.g. blocks and green spaces in 1 km^2 , road widths, distance from neighbouring buildings, etc.). Full information on the buildings surveyed and data collected for each neighbourhood is given in the supplementary information (Supplementary Methods 3 and Supplementary Note). Two street sizes were included, main and secondary streets. To calculate the potential population supported by each simulation (for the fixed area case), the floor area per person for each type of building was used. These values are based on the average floor area per person for owner occupied and social housing domestic dwellings (46 m^2 and 36 m^2 , respectively)³⁹ and office space required per person ($8\text{--}13 \text{ m}^2$)⁴⁰.

To simulate the fixed area urban typologies (Scenario 2), 1000 buildings were simulated with random sizes based upon the representative case study buildings for each of the five building types. Next, the land area is divided into blocks with varying dimensions. Main streets were generated between blocks with widths randomly selected from 13, 14 or 16 m, based on the case studies. Each main block is then divided into smaller lots of land based upon the specified density factor which determines the density of the model. Plots that do not have access to streets are turned into green space. Each plot is then iterated over to place a random building with the target tallness factor of the model into each plot. The criteria for placement are that (i) each building has an area of free space surrounding it, (ii) the height of the building is the closest (typically within a five-metre range) to the target height factor of the model, and (iii) the space between adjacent buildings is 10 m if high-rise whereas low-rise buildings can attach to each other. Plots where no representative buildings could fit were turned into green space. Once an urban typology is simulated based on the specified tallness and density factor, the LCGE is computed for that typology. A flowchart to further support the understanding of the logic behind the model is offered in the supplementary material (Supplementary Methods 2).

To simulate the fixed population urban typologies (Scenario 1), 1000 buildings were simulated for each population as described by Scenario 2. A large land area ($4 \times 4 \text{ km}$, based on analysis of large urban environments such as London, New York City and Shanghai) was generated and divided into blocks of varying dimensions. Blocks, streets and green spaces are generated in the same manner as Scenario 2, for a $400 \times 400 \text{ m}$ grid. The number of possible inhabitants was calculated based on the floor area of the residential buildings divided by the floor area per person required for each building type. Using a recursive algorithm, the initial grid ($400 \times 400 \text{ m}$) is increased by 50 m on each side if the number of people is less than the target number of people for the simulation. Buildings are again sampled, and the total population supported recalculated. Once a tolerance of 50 people is achieved, the model calculates the LCGE of the urban typology. The code used to generate this simulation can be accessed through a GitHub repository linked in the Data Availability section.

The carbon impact of green spaces and transport infrastructure were not included as it is beyond the scope of this study. However, a one-way

ANOVA was conducted to determine the impact of increasing density on road area. A one-way ANOVA was also carried out to determine the impact of building height and density on LCGE, to reduce any uncertainty in the interpretation of the findings. Three hypotheses were tested: (1) Impact of building height on LCGE: H_0 = increasing height does not impact LCGE; H_1 = increasing height does impact LCGE. (2) Impact of density on LCGE: H_0 = increasing density does not impact LCGE; H_1 = increasing density does impact LCGE. (3) Impact of density on road area: H_0 = increasing density does not impact road area; H_1 = increasing density does impact road area. The null hypothesis is rejected for the case of building height; increasing height does significantly impact LCGE. For the case of density and LCGE, the null hypothesis is not rejected; increasing density does not impact LCGE significantly. Likewise, the null hypothesis is not rejected for the impact of road area. The output of each urban typology is the overall density, average height and total LCGE of the stochastic simulation.

Urban density metrics

Urban density is usually referred to as number of people per unit land area inhabiting a given urbanised location. When dealing with urban forms, different approaches exist such as dwellings per hectare or a height centred approach (e.g., floor area divided by land area¹⁵). The latter can be mathematically represented as follows:

$$Df^t = \frac{\sum_{i=1}^n A_i s_i}{A_{Land}} \quad (1)$$

with the numerator in Eq. (1) above representing total floor space as a sum of products between the building footprint area, A , and number of floors, s , for the generic i^{th} building. The main limitation of such a metric is that it does not allow to differentiate between the separate effects resulting from horizontal and vertical densifications. This is graphically illustrated in Fig. 6 where three urban configurations (Cases 1, 2 and 3) score the same urban density (16% as per Eq. (1)); however, they are significantly different if we look at them in terms of land occupation and vertical development. Two separate metrics are therefore required in order to estimate the effect of these two parameters independently. Specifically, we developed two distinct factors for density and height, a “density factor” (Df) and a “tallness factor” (Tf), as defined in equations (2) and (3), where A_i is the building footprint of the generic building i , A_{Land} is the useable land area, H_i is the building height of the generic building i and n is the number of all buildings.

$$Df = \frac{\sum_{i=1}^n A_i}{A_{Land}} \quad (2)$$

$$Tf = \frac{\sum_{i=1}^n H_i}{n} \quad (3)$$

Using the two density factors in Eqs. (2) and (3) above allow for an independent evaluation of the effects that horizontal densification (occupying more of the available land) and vertical densification (building taller) have on urban environments. When density and height are combined, for example expressing density as a function of floor area (e.g. Eq. (1)), two scenarios can have identical urban densities but completely different typologies, thus masking the impact of building type.

Additionally, the density factor we developed always ranges between 0 and 1 (or 100%), thus enabling meaningful comparisons within strict and defined boundaries. The existing metric instead allows density values to exceed 100% (Case 4 in Fig. 6) and potentially has no theoretical upper bound thus limiting further its practical use in comparing the density of different urban typologies.

DATA AVAILABILITY

The data generated and analysed during this study are described in the following data record: <https://doi.org/10.6084/m9.figshare.14663313>⁴¹. All code and supporting data can be accessed via GitHub at <https://github.com/jayarehart/Denser-Taller>. Static versions of the two data files included in the GitHub repository have also been included with the figshare data record⁴¹ (downloaded from GitHub on 24/05/2021). Additional supplementary data and notes are available in the files ‘supplementary_methods.xlsx’ (Excel spreadsheet with multiple tabs) and ‘supplementary_notes.pdf’, which are publicly available in the Mendeley Data repository at <https://doi.org/10.17632/kj3zn5nx6b.1>⁴², as well as together with this figshare data record⁴¹.

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AUTHOR CONTRIBUTIONS

F.P. and B.D. conceptualised the research. R.S. conducted the primary data collection and N.G. developed the parametric model. R.S., N.G. and J.A. developed the methods and performed the analysis. All authors contributed to the discussion and

interpretation of the results. F.P., R.S. and J.A. wrote the manuscript and S.I. All authors reviewed and edited the manuscript and approved the final version.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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