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Mapping material stocks of buildings and mobility infrastructure in the United Kingdom and the Republic of Ireland

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ABSTRACT

Understanding the size and spatial distribution of material stocks is crucial for sustainable resource management and climate change mitigation. This study presents high-resolution maps of buildings and mobility infrastructure stocks for the United Kingdom (UK) and the Republic of Ireland (IRL) at 10 m, combining satellite-based Earth observations, OpenStreetMaps, and material intensities research. Stocks in the UK and IRL amount to 19.8 Gigatons or 279 tons/cap, predominantly aggregate, concrete and bricks, as well as various metals and timber. Building stocks per capita are surprisingly similar across medium to high population density, with only the lowest population densities having substantially larger per capita stocks. Infrastructure stocks per capita decrease with higher population density. Interestingly, for a given building stock within an area, infrastructure stocks are substantially larger in IRL than in the UK. These maps can provide useful insights for sustainable urban planning and advancing a circular economy.

1. Introduction

Construction, maintenance and use of societal material stocks such as buildings and infrastructures are major drivers of resource use and emissions (Krausmann et al., 2017; Lanau et al., 2019; Pauliuk and Müller, 2014). The presence and spatial patterns of buildings and infrastructure determine societies' future resource use and are hence under increasing scrutiny to inform transformative strategies towards more sustainable resource use, climate change mitigation and achieving the Sustainable Development Goals (Haberl et al., 2023; IPCC, 2022; Lanau et al., 2019; Thacker et al., 2019; UNEP-IRP, 2019).

While research on societal material stocks has proliferated in the last years, spatially explicit high-resolution and thematically detailed maps of material stocks at national to global scale are still scarce, limiting the understanding of the role of spatial patterns, material quantities and types (Fu et al., 2021; Lanau et al., 2019). Such maps are valuable to inform sustainable resource management strategies, spatial planning of infrastructure and settlements (Pomponi et al., 2021), improved refurbishment and maintenance strategies, as well as future urban mining and recycling of end-of-life waste from buildings and infrastructure demolition in a more sustainable circular economy (Leipold et al., 2023; Wuyts et al., 2022).

The United Kingdom (UK) and the Republic of Ireland (IRL) are an interesting case study for the following reasons. Recent research for the

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UK suggests a substantial slow-down of the growth of material stocks of buildings, infrastructure and machinery at ~1 % per year, combined with strongly increasing amounts of end-of-life materials, as well as substantial reliance on international trade to import raw materials and export end-of-life materials (Streeck et al., 2020). In the UK, approximately 370 Mt/year of materials are used in the construction sector, 60 % of which are aggregates, 22 % concrete, 10 % asphalt, 4 % iron and steel. In the UK and IRL there is an increasing recognition for the need to address material stocks directly, for example through improved spatial planning, as well as by renovating, converting and upgrading existing buildings instead of demolishing and re-building, to achieve net-zero carbon emissions from the construction industry (Drewniok et al., 2023b; UK Green Building Council, 2021). There is also a growing need by professionals in the circular economy (CE) domain to understand the materials that make up the existing building and infrastructure stock to facilitate measures aiming to re-use, re-purpose, repair and refurbish, instead of simply demolishing them. Therefore, a consistent understanding of the spatial patterns and quantities of material stocks of buildings and infrastructures across the entire country is required to develop resource efficient strategies for maintaining and transforming existing material stocks, in a way which addresses social needs and reductions in resource use to comply with climate and land-related policy targets (Cabrera Serrenho et al., 2019; Drewniok et al., 2023b; Li et al., 2022; zu Ermgassen et al., 2022). So far, however, spatially explicit stock research for the UK and IRL have only been conducted for local areas and specific materials (Ajayebi et al., 2021, 2020; Li et al., 2022; Romero Perez de Tudela et al., 2020; Tanikawa and Hashimoto, 2009), or as part of an Europe-wide mapping at 1 km^2 resolution (Peled and Fishman, 2021). This leaves a substantial knowledge gap regarding national-level material stocks quantities, types, and patterns across the United Kingdom and the Republic of Ireland.

Mapping material stocks requires a consistent integration of multiple and diverse data streams and specific domain expertise. This includes explicit information on surface area sealed by buildings and infrastructure, building footprints, heights and volumes, and, ideally, the type of stocks and material compositions (Lanau et al., 2019; Tanikawa et al., 2015). Sourcing data on the material composition of various stock types at a harmonised resolution consistent with spatially explicit information on buildings and mobility infrastructures remains an important challenge for mapping stocks (Schiller et al., 2019; Sprecher et al., 2021; Zhang et al., 2022). Cadastral data, official 3D city models and light detection and ranging (LiDAR) data can provide such information (Ajayebi et al., 2020; Miatto et al., 2019; Schandl et al., 2020; Tanikawa and Hashimoto, 2009). However, such data is usually not available for entire countries, or is inaccessible. Additionally, the quality, resolution, and source of cadastral data varies widely, being sometimes based on full 3D light detection and ranging (LiDAR), photogrammetry, or census data. The level of detail in different cadastral data acquisition approaches can, additionally, be very different across data providers (Biljecki et al., 2023; Lei et al., 2023; Milojevic-Dupont et al., 2023). While Night-Time Lights (NTL) are increasingly used to map material stocks up to the continental scale (Peled and Fishman, 2021), they provide only relatively coarse resolution (i.e., ~1 km^2), and face limitations regarding their ability to capture non-illuminated stocks such as roads, discern changes in lighting systems from actual stock changes (e.g. from incandescent to LED), as well as saturation and radiometric blooming effects. Recently, these challenges were addressed by some of the authors by developing a novel approach drawing on the latest generation of multi-spectral Earth Observation satellite missions as well as OpenStreetMap, yielding national level, material stock maps at high-resolution of 10 m, applied for Germany, Austria (Haberl et al., 2021), and the USA (Frantz et al., 2023).

In this study, we transfer and adapt this high-resolution large-area stock mapping approach and apply it to the United Kingdom (UK) and the Republic of Ireland (IRL), for the year 2020. In this workflow we transfer methods to the UK and IRL established previously, to first map built-up areas (Schug et al., 2020), building heights (Frantz et al., 2021), and building types at 10 m resolution (Schug et al., 2022, 2021), utilizing freely available Earth Observation data (Sentinel 1 + 2), OpenStreetMap (OSM) and national specific reference training datasets. We then derived material stocks information from these data using material intensity factors specifically compiled for this mapping. This way, we could differentiate 9 building types, 32 infrastructure types and 12 materials. We address the following research questions:

- What are the spatial patterns of material stocks of buildings and mobility infrastructure in the United Kingdom and the Republic of Ireland?
- What mass of different materials are accumulated in buildings and mobility infrastructure?
- How do buildings and mobility infrastructure stocks relate to population density?

2. Methods and data

We developed national specific data to map stocks of buildings and mobility infrastructure for the UK and IRL, and adapted a previously established high resolution stock mapping method (Haberl et al., 2021) to the specifics of the UK and IRL (Figure). We combined three fundamentally different types and sources of data: (1) Earth Observation (EO) data which enables characterizing buildings with regard to their built-up area, vertical extent and type of stock derived from Copernicus Sentinel-1 and -2 satellite imagery via Machine-Learning methods; (2) infrastructure data from crowd-sourced OSM data; and (3) Material Intensity (MI) factors representing the amount [kg] of materials per unit area [m^2] and volume [m^3] of each specific type of infrastructure or building, compiled from the literature and primary databases.

Our workflow can be summarised as follows (Fig. 1): We generated rasterised infrastructure data, that is the fraction cover of infrastructure within a 10 m pixel, from recent OSM vector data (acquired in 2023). We additionally generated impervious fraction cover for the entire study area at 10 m resolution, using a machine learning regression approach, and all available optical Sentinel-2 and radar Sentinel-1 satellite data from 2020, and subtracted rasterised infrastructure data. We composed building footprint data for the study area using reference building footprints derived from the Great Britain Ordnance Survey (Rae, 2017) for Great Britain, which we rasterised at 10 m resolution. As such data was not available for Ireland and Northern Ireland, we empirically deducted a ratio of buildings and other impervious area (without infrastructure) in Great Britain, and applied this factor to the impervious fraction dataset in Ireland to derive building area. We then predicted height for all pixels with building area > 0 %, again using machine learning regression, all Sentinel-1 and -2 observations from 2020, and reference building heights from selected counties for training. Rasterised 2D building data and type were merged to derive building volume. We predicted the type of buildings using the same Sentinel-1 and -2 data and a Random Forest classification with manually collected training data for four classes. Material intensity factors were applied to the building volume data according to building type, and to rasterised infrastructure classes. Below, we also provide an overview on main data sources, processing steps and assumptions for each of these sources (Table 1), as well as information on resolution and accuracy. More documentation on calculation procedures and the validation of results can be found in the Supplementary Information and the Supplementary Data.

2.1. *Mapping stocks based on earth observation and openstreetmaps (OSM)*

First, the total built-up impervious area in the UK and IRL was mapped from Sentinel-2 and Sentinel-1 data, at a spatial resolution of 10 m with a regression-based spectral unmixing approach (Okujeni et al., 2017). We transferred the workflow and model developed in previous

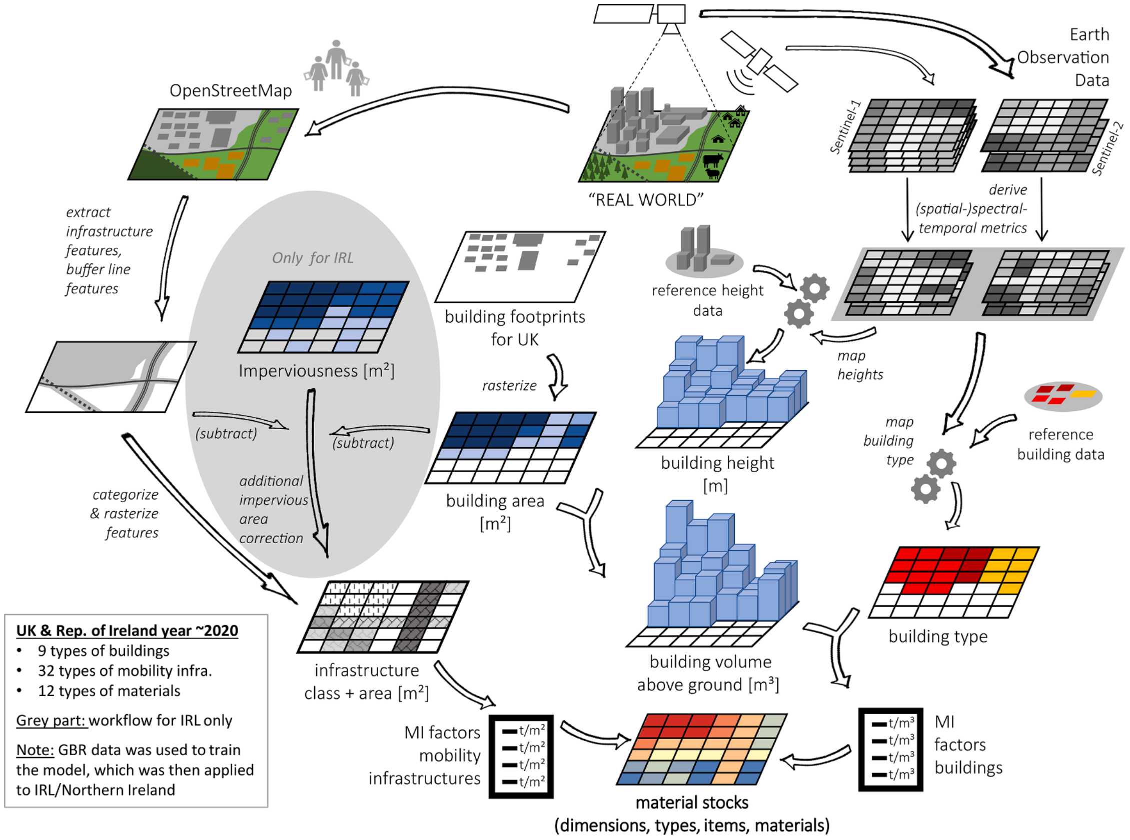

Fig. 1. Workflow used for mapping material stocks in the UK and IRL at high resolution. *…. As of 08/2023, only for some small areas exogenous buildings footprints data is available for IRL, therefore we opted for a consistent approach for the entire IRL, which was tested for its robustness – see supplementary information. Fig. 1 was adapted from (Haberl et al., 2021).

work for Austria and Germany to our study area (Schug et al., 2020). Second, we acquired spatially explicit vector data on road and rail-based mobility infrastructure extent and types from OSM (Geofabrik, 2022). All line data were buffered with infrastructure type-specific widths, rasterised, and multiplied with type-specific material intensity factors (see Section 2.2. and supplementary information).

Third, we acquired building area using building footprints from the Great Britain Ordnance Survey (Rae, 2017). For IRL and Northern Ireland, complete building footprint data was not available, which is why we first subtracted above-ground OSM infrastructure area from the previously mapped impervious area, then split the remaining area into buildings and other impervious areas, using a ratio of 0.49, as in the previously established workflow (Haberl et al., 2021). This ratio was empirically derived from data for GBR where reliable building footprints were available. There, at 1 km resolution, 49 % of impervious area which is not infrastructure as reported in OSM consisted of building area; the remainder being parking lots, driveways and other sealed surfaces.

Building heights data was generated using the approach outlined in (Frantz et al., 2021). We first acquired training data from three-dimensional building footprints for 25 counties or unitary authorities in England (Emu Analytics, 2021), and meticulously screened the data for non-plausible entries. We trained a Support Vector Regression with Sentinel-2 and Sentinel-1 image time series data as explanatory variables to predict the height of every building in the UK and IRL. For landmark buildings and skyscrapers, we used the reported architectural height from the tall buildings database ($n = 535$) (SKYDB, 2021).

We additionally discerned nine different building types. Thereof, we directly mapped four building types using a random forest classifier previously developed for building type detection (Schug et al., 2021), which was trained with manually sampled reference data from twelve regions across Great Britain and Ireland ($n = 1616$ samples). The four types were Low and Medium Density Buildings, Industrial, Retail and Heavy Industry, Buildings in Dense Urban Areas, and light structures such as cabins or huts. In addition, skyscrapers were derived from the skyscraper database (SKYDB, 2021). Height cut-offs between building types (e.g. low-rise versus multi-story buildings at low overall buildings density) were then used to split these five initially identified building types into nine final building types, based on architectural insights on typical height differences across construction styles within the same building type (see Section 2.2. and supplementary information Section 2 and 7) for details and satellite imagery for examples of these buildings types). The nine final building types differentiated can be found in (Table 2).

Material intensity factors were developed from information specific for the UK, and then transferred to IRL, complemented by international information where required (Table 2). These material intensity factors account for, a) the foundations of buildings in relation to the building footprint as expressed via m^2 of built-up area, b) walls and roofs of buildings in relation to the above-ground building volume as expressed in m^3 of modelled building volume, and c) various infrastructures in relation to the built-up area expressed as m^2 of covered surfaces per pixel. Furthermore, on the most detailed level we differentiated 7 components across all buildings: roofs, external and internal walls, foundations, ground and upper floors, and frames. Detailed information on these material intensity factors and a break-down by materials, stock types and components can be found in the supplementary information and supplementary data.

Table 1
Summary of workflow steps, key information and main sources utilised.

Workflow steps	Key information	Data and methods
Impervious area	Machine learning regression using Sentinel-1 and 2	(Schug et al., 2020)
Infrastructure extent and types	Rasterised, buffered and grouped OSM vector data	OpenStreetMap (OSM) processed via procedures adapted to UK and IRL, based on (Haberl et al., 2021)
Building area	• GB = Ordnance survey of building footprints • IRL + NIRL = (Built-up area − Infrastructure area) * 0.49. This additional impervious area correction factor was calibrated on UK data*	 (Haberl et al., 2021; Rae, 2017)
Reference height data	Building heights for 25 counties and unitary authorities	(Emu Analytics, 2021)
Building heights	Machine learning support vector regression model using Sentinel-1 and Sentinel-2 earth observation data	(Frantz et al., 2021)
Skyscrapers	Location and height sourced directly	(SKYDB, 2021)
Building volumes	Building area * building heights, simplified to a LoD1 representation of a building as a cube	(Frantz et al., 2021; Haberl et al., 2021)
Building types	Random forest classification and height cut-offs, based on manually labelled training and validation data as well as national architectural information	(Schug et al., 2021) and Table 2
Material intensity (MI) factors	Building and infrastructure type specific material intensities derived from national and international sources	See Table 2 and supplementary information & data.

2.2. *Validation and robustness of intermediate data and results*

Quantifying data quality and uncertainty is challenging because multiple data streams and methods are integrated, including multiple intermediate data products. We opted for a step-by-step quality assessment, where intermediate data across the workflow were validated against independent data as described in the respective methodological publications (Table 1), recognizing partial incompleteness and differing system boundaries. The intermediate mapping products and methods as well as the overall workflow were independently validated in the respective methodological publications (Frantz et al., 2021; Schug et al., 2020). OSM-derived network lengths for roads and railways were compared against reported lengths in official statistics for the UK and IRL (supplementary information Section 3). For railways, official statistics report only slightly lower network lengths as derived from OSM. For roads, network lengths from OSM are almost double in the case of the UK, mainly due to local roads. This significant difference between OSM and official statistics, may be explained by official statistics only accounting for public roads and not those privately managed or some types of roads, such as tracks, not being considered in official records. Differences in higher-class roads (motorway, primary, secondary, and tertiary) may be due to varying practices in classifying roads by OSM contributors. Finally, we compared the mapped stock estimates against the literature and find good agreement and well explainable differences (see results Section 3.1. and supplementary information Section 1 for details).

3. Results

3.1. *A map of material stocks of buildings and infrastructure*

We find that in total 19.8 Gt of materials, or 279 t/cap, are stocked in buildings and mobility infrastructure across the UK and IRL (Fig. 2). The highest stock density (t/area) prevails in the metropolitan areas, with their largest concentration in England, especially in the Greater London area. Material stocks are largest in England and lowest in Scotland, where only a sparse road network and few large settlements exist. Stocks are clearly more dispersed in Ireland due to more dispersed spatial patterns of settlements, with only two major spikes in the metropolitan regions of Dublin and Belfast (left hand side of Fig. 2). When moving from the national scale shown at 100 m resolution to retain legibility (Fig. 2a), to the full high resolution of 100 m (Fig. 2b) and 10 m (Fig. 2c), it becomes clear why high resolution maps contain useful and consistent information at local, regional, to national scale. Total material stocks of building and mobility infrastructure are displayed in Fig. 1a and b for the Greater London and the Liverpool/Manchester metropolitan regions; the complete high-resolution maps of all stock types and materials can be found in the supplementary data files. London has by far the highest and most widespread buildings stock density, while the greater Liverpool/Manchester area shows a more dispersed pattern. In contrast, the density of the mobility infrastructure is similar in both subsets – although underground subway systems combined with road infrastructure considerably increase the material stock density in parts of London. The 10 m high-resolution maps even enable first-order assessments of the materials contained in specific local buildings, which is highly useful for stakeholders and actors in specific projects, as well as for regional waste management planning.

3.2. *Material stocks by regions, materials and stock types*

We find that 17.3 Gt, or 264 t/cap are stocked in the UK, while IRL has a stock of 2.5 Gt or 475 t/cap (Fig. 3a). Taken together, most of these stocks are aggregates in foundations and sub-base layers of roads at 12.1 Gt, while an additional 4.3 Gt of concrete and bricks are primarily found in buildings. Metal stocks amount to 0.3 Gt, mostly iron and steel with 0.29 Gt. The remaining stock is made up of 0.22 Gt of fossil-fuel-based materials, 0.25 Gt of biomass-based materials, and 0.35 Gt of other minerals and materials such as insulation.

With 11.8 Gt, mobility infrastructure makes up the majority of total material stocks (59 %) in the UK and IRL (Figure). Road infrastructure is estimated at 11.6 Gt, of which parking and other impervious surfaces account for 3.1 Gt, constituting 26 % of all mobility infrastructure stocks usually not reported in official road statistics. The latter category represents all sealed surfaces such as parking lots, driveways and other sealed surfaces not explicitly mapped as roads, rail-based infrastructure, airport runways and buildings. Buildings account for 7.9 Gt or 41 % of total material stocks, dominated by low-rise residential and commercial buildings with 4.2 Gt (53 % of buildings, or 21 % of total stocks), followed by high-rise residential (10–75 m) and industrial or retail buildings with 1.6 Gt (20 % of building stocks) and 1.1 Gt (14 %), respectively.

3.3. *Robustness and validation of stock estimates*

When comparing the results presented herein for the year 2020 with the literature, we found good agreement with previously published country-specific (Drewniok et al., 2023a, 2023b; Streeck et al., 2020; zu Ermgassen et al., 2022) and international studies (Cao et al., 2017; Müller et al., 2013; Pauliuk et al., 2013; Wiedenhofer et al., 2021, 2015); with notable discrepancies only found for a NTL-based European wide mapping (Peled and Fishman, 2021); see supplementary information for detailed comparisons. Using an inflow-driven stock modelling approach,

Table 2

Overview of the main material intensity factors per stock type for buildings (MI in kg/m^3, height in meters), and roads and rail-based infrastructure (MI in kg/m^2, width in meters). Detailed OSM key-specific MI factors were used for mobility infrastructure stocks. Values for roads represent averages of key-specific MI factors (High-class = motorway, trunk, primary secondary; Low-class = all other except for gravel). The category 'Other' includes, among other materials, and timber. Refer to the supplementary information for a complete table of MI factors for all OSM keys and additional structures (bridges, tunnels), materials, and data sources.

Material stock types		Height/ width (m)	Overview of material intensities utilised							Sources
			Metals	Concrete	Bricks	Aggregate	Bitumen	Other	Total	
Buildings (kg/m^3)	*Low to Medium Rise Buildings, Low Density (LM_LDB)*	<10	–	53	232	–	–	13	297	own estimation, see suppl. info
	Medium to Large Rise Buildings, Low Density (ML_LDB)	10–30	10	198	18	–	–	54	279	Adapted from (Drewniok et al., 2023a, 2023b)
	High Rise Buildings, Low Density (HR_LDB)	30–75	14	250	3	–	–	57	324	
	Skyscrapers (SKY)	>75	34	294	–	–	–	9	337	(Frantz et al., 2023)
	Industrial, retail and heavy industry (IRH)	–	18	26	18	–	–	6	67	Adapted from (Drewniok et al., 2023a, 2023b)
	Low to Medium Rise Buildings, Dense Urban (LM_DUB)	<10	29	257	150	–	–	19	455	
	Medium to Large Rise Buildings, Dense Urban (ML_DUB)	10–30	49	190	–	–	–	16	255	
	High Rise Buildings, Dense Urban (HR_DUB)	30–75	49	187	–	–	–	16	252	
	Light structures (LIGHT)	–	2	147	–	67	–	57	273	(Haberl et al., 2021)
Roads (kg/m^2)	*Motorway*	33.1	–	–	–	1470	25	–	1496	UK and IRL road construction standards, see suppl. information
	Motorway (link)	11.3	–	–	–	1534	27	–	1561	
	Trunk (A-road)	25.7	–	–	–	1452	25	–	1477	
	Trunk (link)	11.3	–	–	–	1534	27	–	1561	
	Primary	19.6	–	–	–	1568	34	–	1602	
	Primary (link)	9.3	–	–	–	1698	38	–	1735	
	Secondary	7.3	–	–	–	1524	30	–	1554	
	Secondary (link)	7.3	–	–	–	1524	30	–	1554	
	Tertiary	6.0	–	–	–	1538	30	–	1568	
	Tertiary (link)	6.0	–	–	–	1538	30	–	1568	
	Residential	6.0	–	–	–	1538	30	–	1568	
	Living street	5.5	–	–	–	1300	25	–	1325	
	Pedestrian	4.8	–	–	–	1300	25	–	1324	
	Footway	2.0	–	–	–	382	8	–	390	
	Cycleway	3.5	–	–	–	382	8	–	390	
	Other	4.5	–	–	–	1538	30	–	1568	
	Gravel	4.5	–	–	–	304	2	–	306	(Haberl et al., 2021)
	Parking areas	–	–	–	–	1538	30	–	1568	UK and IRL road construction standards, see suppl. information
	Motorway on bridge	30.0	–	–	–	516	25	–	541	
	Box (motorway on bridge)	33.1	217	3955	–	567	–	–	4739	Adapted from (Watt, 2019)
	Other bridges	–	402	2713	–	637		–	3752	
	Road on bridge	–	–		–	276	15	–	290	
	Road tunnel	–	172	4557	–			–	4729	(Haberl et al., 2021)
Rails (kg/m^2)	*Railway*	12	15	13	–	365	–	2	395	(Network Rail UK, 2020)
	Subway underground	8	655	13,189	–	–	–	–	13,843	Adapted from (Lederer et al., 2016)
	Subway ground (bridge)	8	362	4614	–	428	–	–	5404	
	Subway ground (surface level)	8	255	2338	–	428	–	–	3021	
	Tram/other	7	18	557	–	40	–	–	615	Adapted from (Gassner et al., 2018)
	Railway bridge	12	495	2431	–	685	–	–	3610	Adapted from (Watt, 2019)
	Railway tunnel	12	153	4070	–	–	–	–	4224	(Haberl et al., 2021)

Streeck et al. (2020) estimated 18 Gt of total material stock for the United Kingdom in the year 2017, which includes machinery and other products which are out of scope herein, while the presented estimate of buildings and mobility infrastructure amounts to 19.8 Gt for the year 2020. For non-metallic construction minerals representing the bulk of materials in building and mobility infrastructure, this study estimated 19 Gt, while (Streeck et al. 2020) report 16.8 Gt. In comparison to international studies, the mapped estimate 4 Gt of concrete compares well against UK concrete stock estimates of 5.5 and 5.3 [4.3–5.8] Gt from (Cao et al., 2017; Müller et al., 2013). Iron and steel stocks in the UK estimated herein amount to 0.3 Gt, which is notably lower than the 0.8 [0.6–0.9] and 1.0 Gt from (Müller et al., 2013; Pauliuk et al., 2013), mostly because iron and steel have multiple end-uses not covered herein, such as vehicles, machinery and other products. For buildings and mobility infrastructure, our estimate of 17.3 Gt is about twice as large as the 7.6 Gt from (Wiedenhofer et al., 2015), because of more refined and nationally specific material intensities were used herein, and because Wiedenhofer et al. (2015) utilised officially reported data on floor area and extent of mobility infrastructure, which are known to underreport. Finally, a night-time lights-based stock mapping approach from (Peled and Fishman, 2021) yielded 10.5 Gt of material in the UK and Ireland, compared to the 19.8 Gt estimated herein. We therefore conclude that the estimates presented herein are robust and in good agreement with most previous work, where remaining differences are well explainable. We refer to the supplementary information for more detailed comparisons and discussion.

3.4. Spatial patterns of material stocks

To assess spatial patterns, we use population data gridded in a 1 km^2 raster across the UK and IRL (Schiavina et al., 2023), and aggregate material stocks from the original 10 m maps to the 1 km grid cells. Plotting those results as boxplots shows that the majority of grid cells across nearly the entire spectrum of population density have

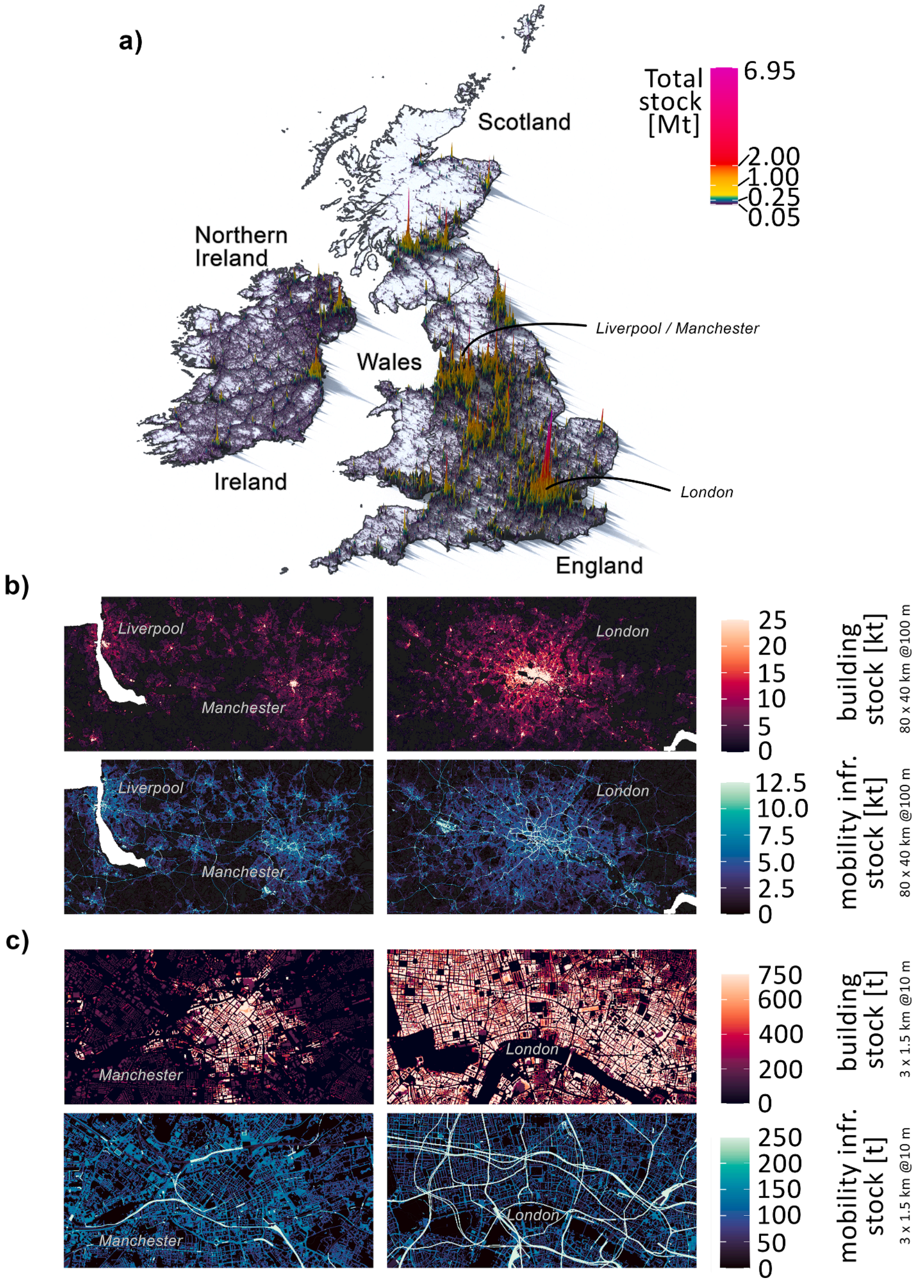

Fig. 2. Three-dimensional map of material stocks in buildings and mobility infrastructure in the UK and IRL; with two-dimensional subsets of the Liverpool/ Manchester and London metropolitan areas showing a breakdown into building and mobility infrastructure stocks. For the purpose of these visualisations and to maintain readability, the resolution of the 3D map is 1 km (a), and the 2D maps are 100 m (b) and 10 m (c), respectively. See supplementary data for the full national-level wall to wall 10 m high-resolution maps.

approximately building stocks of ~80–100 t/cap, with minimal differences between England, Scotland, Wales and Northern Ireland (UK), and the Republic of Ireland (IRL) (Fig. 4a). Only areas with minimal population density have substantially larger and much more variable building stocks per capita. We do note a slightly decreasing variability of building stocks per capita at higher population densities, however it is unclear if this is a methodological artefact from mapping population (Schiavina et al., 2023), and/or data limitations in mapping material stocks; the same issues apply to the grid cells with extremely low stocks capita (lower end of boxplot whiskers).

Regarding building stocks per area, the majority of grid cells from low to intermediate population density follow an exponential relation with building stocks per area (Fig. 4b). For the highest population densities of >5000 cap/km^2, a noticeable upward increase can be seen, where disproportionally larger stocks as well as a higher variation of stocks per area is found, than in all other areas with less population density. Interestingly, higher population density does not result in (substantially) lower building material stocks per capita (Fig. 4a). This might be due to denser areas also containing increasingly more commercial and public buildings next to residential living space, as well as that taller buildings do not necessarily translate into substantial savings in material stocks per capita.

For mobility infrastructure stocks a negative relation with population density is found (Fig. 4c). Areas with very low population density

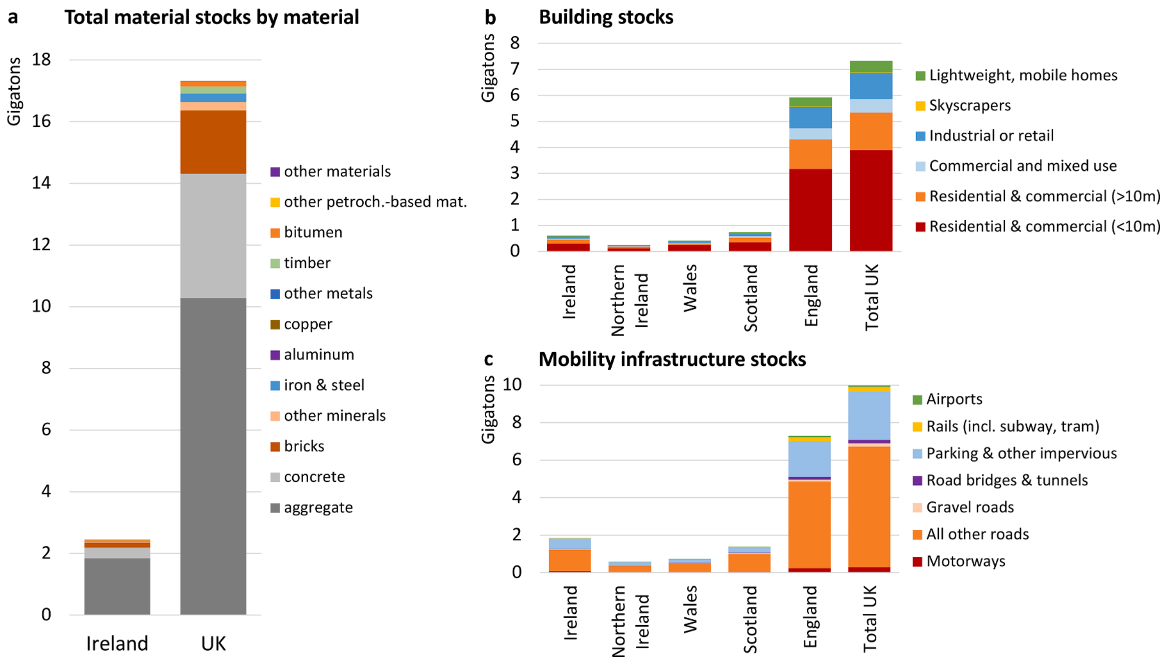

Fig. 3. Material stocks of buildings and mobility infrastructure in the UK and Ireland for the year ~2020.

have 2–3x times the per capita infrastructure stocks than areas with intermediate to high population density, indicating an exponential decrease of infrastructure requirements per capita with higher population density. All regions across the UK and IRL follow this pattern, with IRL and Northern Ireland having slightly higher infrastructure stocks per capita than other UK regions at a similar population density. Per area, infrastructure stocks show a similar positive exponential relation as for building stocks (Fig. 4d). In summary, we find a clearly negative relation of infrastructure stocks per capita with increasing population density.

We do note however that the gridded population data used above also has potential limitations because it was disaggregated from census and administrative units to grid cells, informed by the distribution and density of built-up as mapped in the Global Human Settlement Layer (GHSL) global layer (Schiavina et al., 2023). However, independent census data is only available for local administrative units, which are very heterogeneous in size and their numbers differ by a factor of ten between IRL and the UK, limiting comparability.

3.5. Scaling of buildings and mobility infrastructure stocks across the UK and IRL

To dive deeper into the scaling of buildings and infrastructure stocks across population densities and test for the robustness of these findings across spatial scales, we regressed building and infrastructure stocks across gridded 1 km^2 and 10 km^2, as well as for local administrative units (LAU) (Fig. 5). Interestingly, for the UK we find a similar relation between buildings and infrastructure stocks at the 1 and 10 km^2 resolution, with a slope of 0.68 and 0.7 (R^2 of 0.72 and 0.84, Fig. 5a,b). For the LAU, the relationship in the UK becomes stronger with a slope of 0.96, however with a much larger scatter, reflected in a lower R^2 of 0.49 (Fig. 5c). In IRL a substantially stronger scaling of infrastructure with buildings stocks is found than in the UK, with a slope of 1.01 at 1 km resolution (R^2 of 0.77, Fig. 5d). At the 10 km^2 and LAU aggregations, this relationship becomes even more pronounced, with a slope of 1.12 and even 1.92, with high R^2's of 0.88 and 0.94 (Fig. 5e,f).

This indicates that for a given building stock, infrastructure stocks tend to be larger in IRL than in the UK. Infrastructure stocks scale more than proportional with building stocks across population densities (slopes of >1), while in the UK they scale less than proportional (slopes of <1). The directions and strengths of these relationships are clearly robust across different levels of spatial aggregation (Fig. 5). These findings show the impacts different settlement patterns have on the required material stock. IRL and Northern Ireland are dominated by two large cities and the remainder of the island is settled in smaller villages and towns, requiring substantially more mobility infrastructure. In the UK, there are multiple large cities dispersed around England and Wales, with very sparsely settled regions only in northern Scotland.

4. Discussion

This study presents the first national-level maps of building and infrastructure material stock patterns across the United Kingdom (UK) and the Republic of Ireland (IRL), which are freely available in the supplementary data at 10 m resolution.

4.1. Spatial patterns of material stocks

We surprisingly find that building stocks per capita are relatively similar across population densities in both countries, with the main exemption being very sparsely settled areas (Fig. 3). For mobility infrastructure stocks per capita, we do find a clearly negative relation of higher population density having less stocks per capita; which reflects more intensive use of those infrastructures and denser networks connecting relatively more people and places. Less populated areas have significantly more infrastructure stocks per capita, reflecting the need for more extensive road and rail networks to connect spread-out communities. When comparing how mobility infrastructure and building stocks relate to each other within the same area, we find that in the UK higher building stocks under-proportionally relate to infrastructure stocks (Fig. 4). In IRL this relationship is over-proportional, indicating that more building stocks within a 1 km^2 area come with a proportionally higher amount of road infrastructure stocks, due to more dispersed settlement pattern in IRL than in the UK (Fig. 2).

These findings highlight the distinct patterns of urban, sub-urban and rural areas and how settlement patterns shape the amount of material stocks required for buildings and mobility infrastructure stocks. A

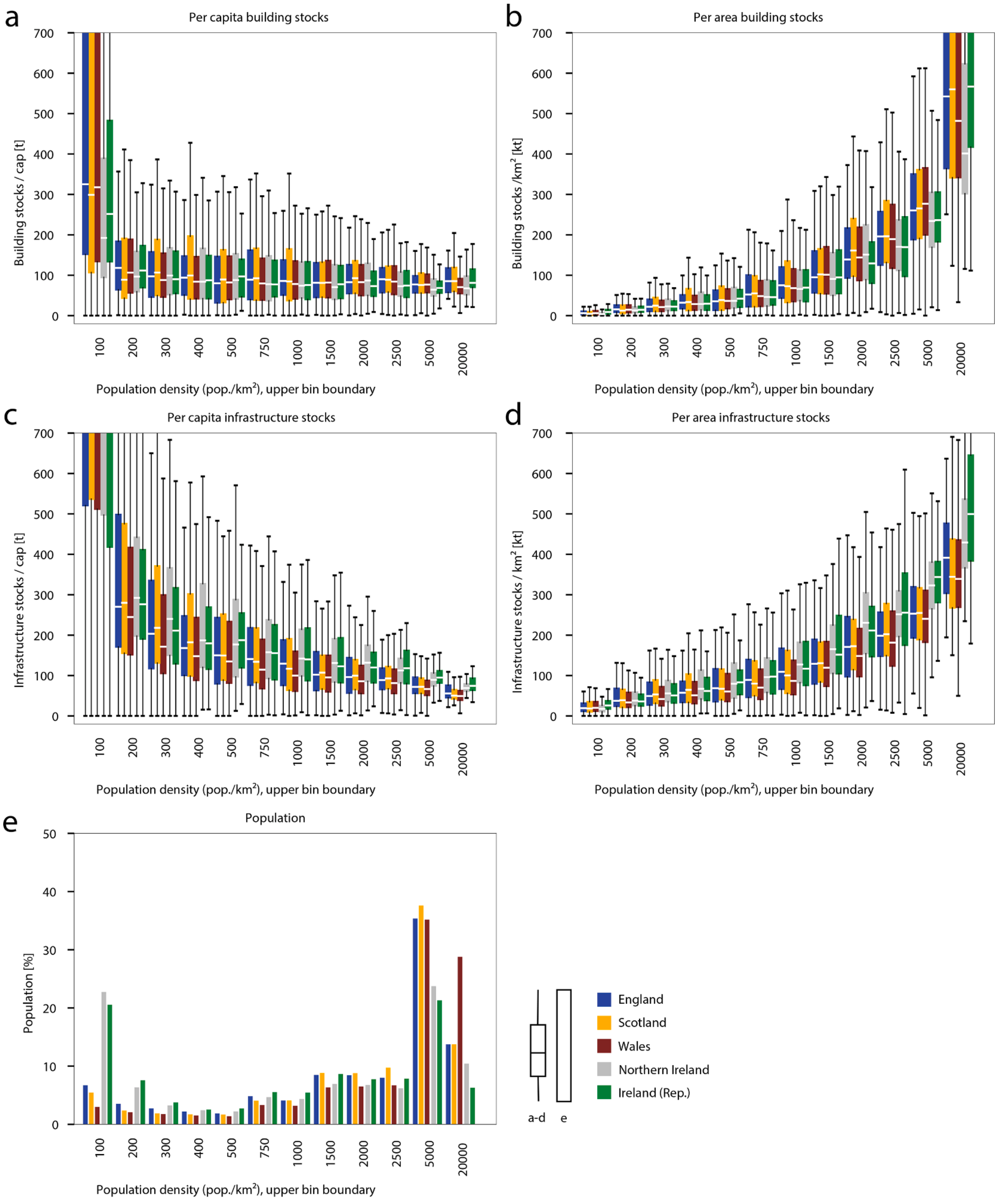

Fig. 4. Building (a,b) and infrastructure (c,d) stock per capita (a,c) and per area (b,d) in England (ENG), Scotland (SCO), Wales (WAL), Northern Ireland (NIR), and Ireland (IRL). e) Share of population living in municipalities with respective population density. Boxplots represent the material stock in all grid cells at 1 km resolution, grouped by population density. Labels of the x-axis represent the upper boundary of the boxplot bins, e.g., 500 for all areas with a population density between 400 and 500. Please note that the box covers 50 % of all data points, while the whiskers above/below each contains 25 % of data points. The line in the box represents the median value. Rasterised population data for 2020 was sourced from the latest update of the Global Human Settlement Layer (Schiavina et al., 2023). For an enlarged version without cut-off at the higher end, see the supplementary information.

deeper understanding of these differences and similarities requires in-depth research on the historical dynamics of settlement growth over the last hundreds of years, as both UK and IRL have been settled since pre-historical times and substantial spatial path-dependencies going back to at least Roman road systems can be expected. The historical role of spatial planning, as well as socio-economic dynamics during industrialisation and after WW2 additionally play a major role where settlement growth occurred and where major mobility infrastructure projects reinforced existing settlement patterns. Addressing these reasons therefore requires its own interdisciplinary research efforts, which is beyond the scope of this work.

4.2. Policy implications and practical relevance

The findings presented herein provide new insights into the built environment of the UK and IRL, which can be used for policy-making and planning, particularly for resource management strategies such as the circular economy, spatial planning, and meeting net-zero GHG emissions targets. Substantial amounts of material stocks have been accumulated across the UK and IRL, amounting to 279 tons/cap, with

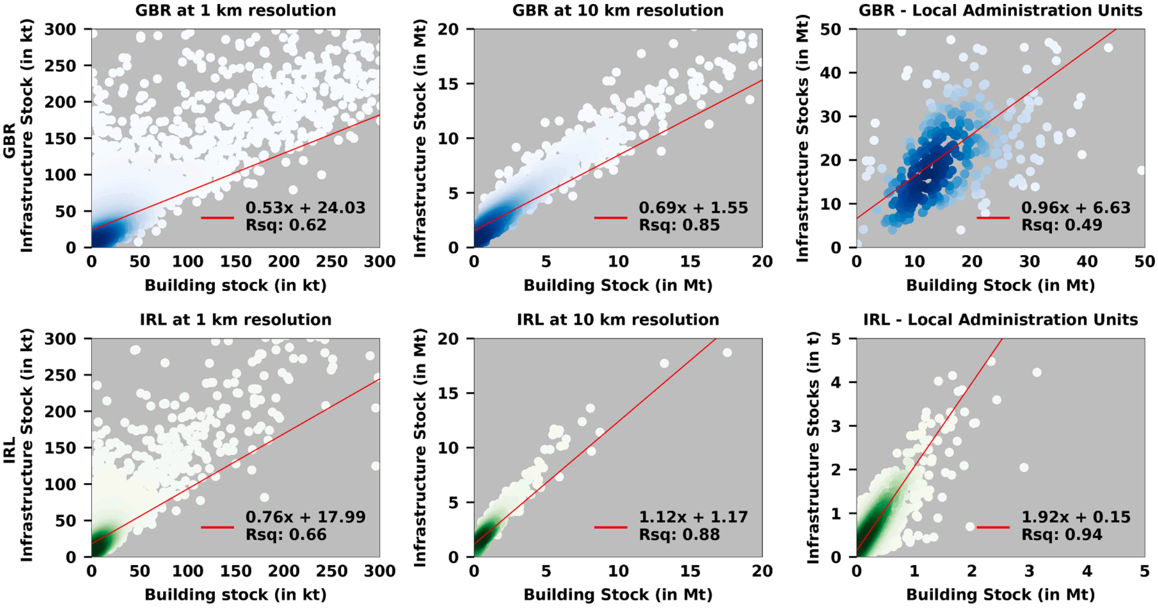

Fig. 5. Relation of total building stock and total infrastructure stock in Great Britain (a–c) and Ireland including Northern Ireland (d–f) at a spatial aggregation level of 1 km (a,d), 10 km (b,e) and Local Administrative Units (c,f). These relationships also hold across different assumptions required to differentiate sealed surfaces into buildings and mobility infrastructure, see supplementary.

large spatial differences (Fig. 2). The majority of stocks is found as aggregates, concrete, and bricks, while metals constitute a much lower weight, however play a crucial role due to the high environmental pressures associated with their production, as well as their economic value. These results also show, insofar available national statistics underreport the amounts of infrastructure and building stocks (see supplementary information Section 3), highlighting the need for an improved evidence base to inform policy and other stakeholders as provided herein.

The presented maps of spatial patterns and quantities of material stocks at 10 m resolution are useful to advance circular economy strategies, as understanding the specific local quantities, compositions and distributions of stocks is crucial to inform local activities aiming to re-use, re-purpose, repair and refurbish existing stocks. These maps also provide a first-order cadaster of potential secondary resources contained in the stock which could be recycled via 'urban mining'. Such information is necessary to inform regionalised construction and demolition waste management strategies, as approximately half of the UK's waste streams are due to building demolition, requiring at least regional management. In recent years, demolition rates of domestic buildings decreased (Drewniok et al., 2023a; zu Ermgassen et al., 2022), while industrial, retail, heavy industry buildings so far followed the cyclicality of the UK economy (McGough and Tsolacos, 1997). Approx. 22 million m^3 of residential dwellings and 17 million m^2 of new non-domestic buildings were added to the UK building stock, while approx. 0.86 million m^2 of domestic and almost 14 milllion m^2 of non-domestic buildings were demolished in the UK (Drewniok et al., 2023b, 2023a), generating approx. 15 Mt/year of construction and demolition waste, 0.3 Mt/year of structural steel and 0.15 Mt/year of steel reinforcement waste. Demolished infrastructure and road projects generate approx. 10 Mt/year of construction and demolition waste, 0.2 Mt/year structural steel and 0.25 Mt/year steel reinforcement. In 2020, the UK generated 59.1 Mt/year of non-hazardous C&D waste, of which 54.8 million tonnes was recovered (DEFRA, 2023). No information whether they were downcycled, recycled or upcycled is available. In 2020, Ireland generated 8.1 Mt/year of construction and demolition waste, most of which was backfilled/downcycled (85 %), while only 7 % was recycled and 8 % was sent for disposal (EPA, 2023). Substantial amounts of demolition waste are therefore occurring each year, which necessitates forward looking planning of the necessary institutional setup, business activities and regionalised physical infrastructure for measures aiming to re-use, re-purpose, repair, refurbish stocks, and recycle materials, instead of mostly downcycling them.

Because the UK and IRL have ageing housing stocks in need of retrofit to increase their energy efficiency, the stock maps are also important inputs to identify hotspots of potential renovation, especially if extended with additional information on spatially explicit energy use for heating and cooling of buildings. These are, however, not available per building, but only for local areas. Alternatively, ground-based multi-sensor scanning of the heat loss of individual buildings across settlements could yield location specific insights into renovation and refurbishment potentials (Arbabi et al., 2022; Dai et al., 2022), which combined with the maps presented herein, could be used to show the material- and energy saving potentials of specific strategies in high spatial detail. As of now however, refurbishment is not systematically incentivised by the current tax and legislative system, at least in the UK. As a result, many buildings are demolished rather than refurbished, leading to unnecessary resource use and waste generation. As the UK aims for net zero carbon emissions from the construction industry by 2050, the environmental benefits of lifetime extension, incl. refurbishing, renovating, and re-using, need to be demonstrated at a large scale, so decision-makers can be convinced of the relevance of changes in policies. This is reflected by the growing interest from built environment professionals in the circular economy, and understanding what materials are housed within the building stock to facilitate building repurposing and material reuse (UK Green Building Council, 2021). This research therefore provides an important evidence base for planning recycling systems and required legislation, e.g. physical storage sites, transport routes, material exchange platforms etc.; as well as for business actors to scope potential secondary resources contained in existing and soon-to-be refurbished/demolished stocks (Wuyts et al., 2022).

The variation in material stock types and quantities across regions also calls for tailored resource management strategies. In areas with a high concentration of specific materials, such as concrete and bricks in more dense areas and urban centres, policies could focus on renovation and refurbishing, next to recycling these materials. In contrast, rural areas might require different strategies, considering their spatially dispersed building stocks and higher infrastructure needs, limiting recycling potentials simply due to much longer transport required to match supply and demand for secondary resources from existing stocks. The high-resolution mapping of material stocks presented herein can therefore significantly enhance the design of circular economy strategies, particularly in the context of building renovation and demolition (Wuyts et al., 2022). By understanding what materials are present and where, policies can be formulated to promote the reuse and recycling of materials, reducing waste and encouraging sustainable resource use. For example, regulations could require a certain percentage of materials in new constructions to be sourced from recycled or repurposed materials. These findings can also inform infrastructure maintenance and development policies. Understanding the existing material stocks can help in planning maintenance schedules, prioritizing areas with aging or overburdened infrastructure, and ensuring resource-efficient upgrades, especially as mobility infrastructure is a widely used sink for construction and demolition waste from buildings.

4.3. Limitations and next steps

Despite the high spatial and thematic resolution of our maps, the results are subject to limitations and uncertainties, particularly on a very local level. For example, while the distinction of nine building types at high spatial resolution is unprecedented, we could only identify archetypes of buildings and infrastructure that likely contain intra-class variation. Based on remote sensing information for the UK and IRL, it was furthermore not robustly possible to discern industrial, retail and heavy industry buildings in more detail, which constitute a substantial part of the stock with generally lower lifetimes than residential buildings. It was also not feasible to assess which stocks are still utilised and how much hibernating, un-used stocks there are. Furthermore, building stocks in IRL and Northern Ireland were estimated using machine learning models trained on the UK, as well as using material intensities derived from mainly UK-specific sources, therefore assuming good transferability (Schiller et al., 2019). Because the UK and IRL have a long-shared history and similar socio-economic and climatic conditions, transferability can be safely assumed. However, for other countries or world-regions, transferability will be more limited, requiring adaptations to the entire mapping workflow given available training data and remote sensing challenges, as well as regionally specific building data. Furthermore, spatially explicit information on the age and quality of buildings and infrastructure would be valuable to also refine the UK and IRL stock maps presented herein, using age-specific building and construction types, enabling modelling regionally refined refurbishment and maintenance strategies and scenarios for future end-of-life materials.

5. Conclusions

This study presents the first wall-to-wall, high-resolution maps of material stocks of buildings and mobility infrastructure for the United Kingdom (England, Wales, Scotland, Northern Ireland) and the Republic of Ireland (IRL), using a consistent method covering residential and non-residential buildings, as well as road- and rail-based mobility infrastructure across the entirety of both countries. Tackling the complexity of integrating diverse data streams and multiple domain expertise into a high resolution 10 m mapping of material stocks for entire countries addresses the need for improved methodologies and empirical findings for sustainability research. Importantly, these findings can be highly useful for urban planning, policy-making, and the advancement of circular economy initiatives. They contribute to the understanding of how societal material stocks can be managed with regionalised strategies to support climate change mitigation, sustainable resource use and achieving the Sustainable Development Goals. These maps also help identifying key areas for future research and policy focus and offer valuable insights for researchers, policymakers, and practitioners working towards a more sustainable and resource-efficient future.

CRediT authorship contribution statement

Dominik Wiedenhofer: Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Franz Schug:** Writing – review & editing, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hannes Gauch:** Writing – review & editing, Resources, Investigation, Formal analysis, Data curation. **Maud Lanau:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Michal P. Drewniok:** Resources, Investigation, Funding acquisition, Formal analysis, Data curation. **André Baumgart:** Validation, Investigation, Formal analysis, Visualization, Writing – review & editing. **Doris Virág:** Data curation, Validation, Visualization. **Harry Watt:** Formal analysis, Investigation. **André Cabrera Serrenho:** Funding acquisition, Resources, Supervision, Writing – review & editing. **Danielle Densley Tingley:** Funding acquisition, Resources, Supervision, Writing – review & editing. **Helmut Haberl:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **David Frantz:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Helmut Haberl reports financial support was provided by European Research Council. Hannes Gauch, Andre Serrenho, Michal P. Drewniok, Maud Lanau, Danielle Densley Tingley reports financial support was provided by Engineering and Physical Sciences Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supplementary data files are fully accessible in the supplementary information and via zenodo after acceptance

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107630.

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