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Policy Analysis

# High-Resolution Mapping of the Urban Built Environment Stocks in Beijing

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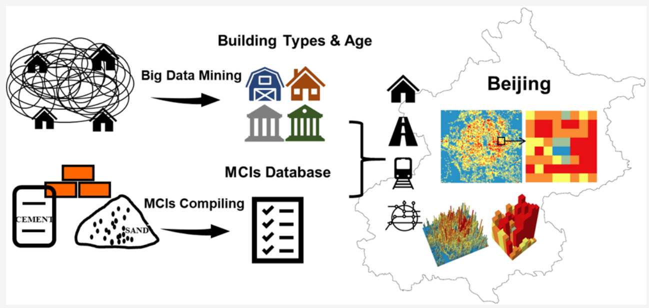
**ABSTRACT:** Improving our comprehension of the weight and spatial distribution of urban built environment stocks is essential for informing urban resource, waste, and environmental management, but this is often hampered by inaccuracy and inconsistency of the typology and material composition data of buildings and infrastructure. Here, we have integrated big data mining and analytics techniques and compiled a local material composition database to address these gaps, for a detailed characterization of the quantity, quality, and spatial distribution (in 500 m × 500 m grids) of the urban built environment stocks in Beijing in 2018. We found that 3621 megatons (140 ton/cap) of construction materials were accumulated in Beijing's buildings and infrastructure, equaling to 1141 Mt of embodied greenhouse gas emissions. Buildings contribute the most (63% of total, roughly half in residential and half in nonresidential) to the total stock and the subsurface stocks account for almost half. Spatially, the belts between 3 and 7 km from city center (approximately 5 t/m$^2$) and commercial grids (approximately 8 t/m$^2$) became the densest. Correlation analyses between material stocks and socioeconomic factors at a high resolution reveal an inverse relationship between building and road stock densities and suggest that Beijing is sacrificing skylines for space in urban expansion. Our results demonstrate that harnessing emerging big data and analytics (e.g., point of interest data and web crawling) could help realize more spatially refined characterization of built environment stocks and highlight the role of such information and urban planning in urban resource, waste, and environmental strategies.






## 1. INTRODUCTION

Urban built environment stocks are crucial backbone of modern civilization[1] as they provide basic services (e.g., shelter and transportation) to humans, set the physical boundary of cities and human activities, and represent secondary material repositories. However, the construction, operation, maintenance, and end-of-life management of building and infrastructure stocks result in increasing energy use and environmental challenges such as greenhouse gas (GHG) emissions and construction and demolition (C&D) waste generation.[2,3] With continued urbanization and population growth over the next decades,[4] a further expansion of urban built environment stocks is expected, especially in developing countries. Therefore, it becomes essential to better understand the patterns, drivers, and impacts of urban built environment stocks and accumulated materials for better resource and environmental management.

The past decade has seen a growing body of literature on built environment and material stocks in various fields,[5] from environmental sciences[6] to social sciences[7] and geography,[8] at global,[9] national,[10] regional,[11] and sectoral levels (in particular road,[12] subway,[13] railway,[14] energy,[15] and water and wastewater networks[16]). These studies provide a first understanding of the overall patterns of built environment stocks, but with few studies on city or subcity levels and without high geographical resolution of stock characterization, they could not reveal the spatial patterns and drivers[1] of materials distribution and accumulation in cities.

Integrating Geographical Information System (GIS) tools and data with Material Flow Analysis (MFA, including both stocks and flows analysis) provides a new perspective that allows for a high spatial resolution characterization and improved understanding of the physical composition of built environment stock.[1] For example, Tanikawa et al. made a first attempt along this line to investigate the spatial and temporal changes of construction material stocks in two case urban areas[17] and further expanded it to all buildings and infrastructure in Japan from 1945 to 2010.[18] Following this, several studies quantified the weight and distribution of building material stocks across cities such as Vienna,[19] Rhine-Ruhr metropolitan area,[20] and Chiclayo.[21] Such spatially refined stock information has been consequently used to

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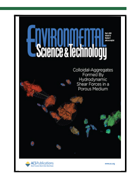

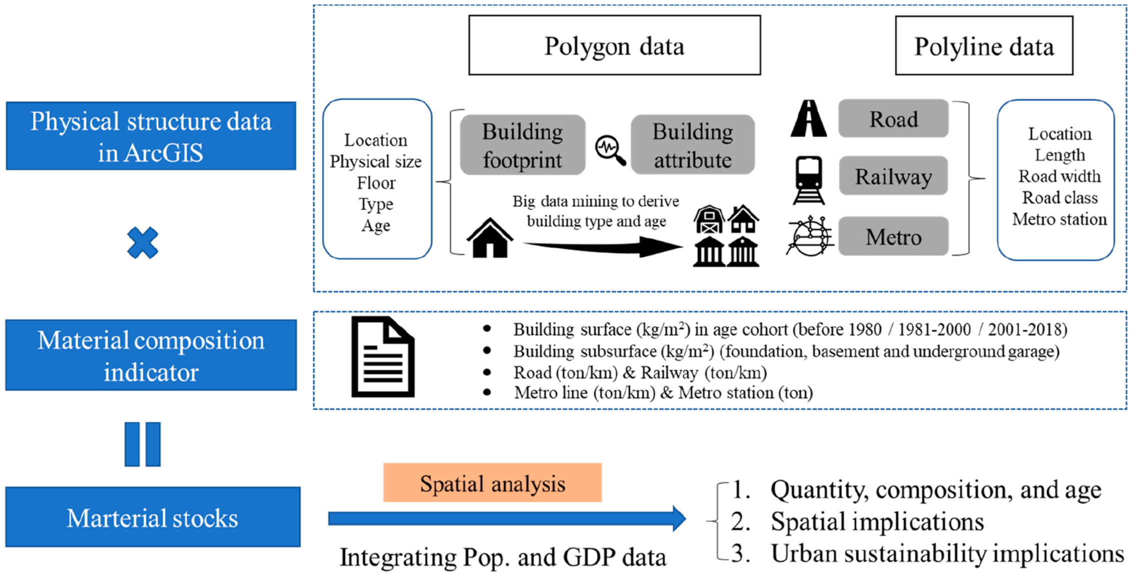


**Figure 1.** Workflow for high-resolution mapping of the built environment stocks in Beijing.

discuss urban mining potentials,[22,23] characterize spatial patterns of stock growth,[24,25] and explore strategies for environmental impacts mitigation[26,27] and C&D waste management.[28,29]

The attributes (e.g., geolocation, typology, and year of construction) and the specific material composition of buildings and infrastructure are the two key parameters in high-resolution mapping and characterization of built environment stocks. However, they are often not consistent or with high uncertainty in previous studies, including:

- Nonresidential buildings (NRBs) are often not counted[30−32] or considered only in a rough way (e.g., assumed an equal share for residential buildings (RBs) and NRBs[33]) in the literature, leading to underestimation of urban built environment stocks. NRBs represent diverse yet key urban functions (e.g., education, healthcare, and commercial) and are important both land area wise and construction material stock wise.[34] A better classification (which is currently lacking[35,36]) and characterization of NRBs can therefore help facilitate better understanding of stocks-flows-service nexus.
- While different urban built environment stocks are heavily interconnected[37] via infrastructure, the important urban infrastructure systems (e.g., road, subway, and railway) are not always fully counted in previous case studies.[33,38,39] This prevents a better understanding of the interaction between buildings and infrastructure, for example in the discussion around spatial versus vertical urban expansion (trading materials for land) and aggregated effects on total materials and energy use in cities.
- Material composition indicators (MCIs),[40] which represents the material composition of buildings and infrastructure, should ideally be specific to each and every building and infrastructure.[1] But as of today, due to data gaps, studies often rely on average MCIs derived from building design codes and guidelines[30,41,42] or refer to results from literature.[43,44] Realizing the importance of MCIs for bottom-up material stock studies, researchers have developed national MCIs databases (e.g., for RBs in Sweden[45]), compiled a literature based global database,[46] and discussed the transferability of MCIs across countries for RBs.[40] However, the lack of region or city specific MCIs data is still a key barrier and results in uncertainty in high-resolution built environment stocks characterization.[1] This is particularly true for cities in developing countries like China, where typology and architecture of buildings can be very different from European (e.g., where RBs are usually classified into single-family and multifamily houses) and Japanese cities (e.g., where more RBs are timber and steel frame based) which are more often reported in the literature.

In this paper, we selected Beijing as a case study to address the above-mentioned gaps. We aim to characterize the quantity, composition, and age of its urban built environment stocks in a high spatial resolution, based on new data science methods and improved MCIs data from various sources, and discuss its implications for urban planning and resource, waste, and environmental strategies under a rapid urbanization process. As the capital of China, Beijing municipality has an area of 16 411 km$^2$ and a population of 21.7 million[47] in 2018. Since the fast urbanization after the reform and opening in 1978, it has witnessed a rapid urbanization and its GDP grew over 250 times.[47] Accordingly, construction in Beijing also showed an unprecedented development especially before the Beijing 2008 Summer Olympics. As a relatively mature city in the world's largest developing country, the insights from this case study of Beijing can be useful both for comparison with cities in industrialized countries and for informing urban sustainability transition in other developing cities.

## 2. MATERIALS AND METHODS

**2.1. Model Framework.** As the overall workflow of this work shown in Figure 1, we combined MFA, GIS, and big data mining and analytics for quantifying the urban built environment stocks in Beijing and revealing its spatial distribution. In summary, the geographical location information and physical size of buildings and infrastructure (roads, metros, and railways) were obtained from AutoNavi Company and big data mining was conducted to collect different building attributes. Then, we calculated the construction material stocks combined with a newly constructed MCIs database, rasterized building stocks in 500 m × 500 m grids, and spatially analyzed their embodied GHG emissions and socioeconomic drivers and implications.

The reference year is 2018, when the latest data are available. We considered 16 types of construction materials (cement, steel, timber, brick (fired clay brick), gravel, mortar, sand, asphalt, lime, mineral powder, fly ash, glass, ceramic, copper, aluminum, and waterproof paint), in which 12 types were found in buildings, 6 types in roads, 8 types in railways, and 8 types in metro.

*2.1.1. Built Environment Stocks Estimation.* The bottom-up approach of built environment stocks estimation builds on two key parameters (see eq 1): (i) the physical size as well as attribute of the built environment components (e.g., m, $m^2$, and $m^3$, detailed in Section 2.2), and (ii) the MCIs specifically to each component (e.g., kg/m, kg/$m^2$, and kg/$m^3$, detailed in Section 2.2).

$$\mathrm{MS}_{m,i,j}(t) = \sum_{m,i,j} (PS_{i,j}(t) \times MCI_{m,i,j}(t)) \tag{1}$$

Where $\mathrm{MS}_{m,\,i,\,j}(t)$ is the stock of material $m$ in construction sector i (buildings, roads, metros, and railways), with the type j (12 building typologies, 4 road classes, railway, metro line, and metro station) in year $t$; $\mathrm{PS}_{i,j}$ (t) is the physical size of construction sector $i$ with the type $j$ in year $t$; and $\mathrm{MCI}_{m,\,i,\,j}$ (t) is the intensity of material $m$ per physical size in construction sector $i$ with the type $j$ in year $t$.

*2.1.2. Embodied Greenhouse Gas Emissions Calculation.* The GHG emission factors of different construction materials taken from life cycle assessment (LCA) database in kg $CO_{2\text{-eq}}$ per $t$ material, which represent the cradle-to-gate requirements needed for raw material extraction, material manufacture, and processing[48] (transport to construction site and construction stages are excluded due to data gaps), were used to calculate the GHG emissions embodied in the built environment stocks. Whenever possible, we used emission data from eBalance,[49] a local Chinese database which has more China specific life cycle inventory data, for each construction material; when data are not available in eBalance, Ecoinvent[50] was used as a supplement source (only for two materials; see in the Supporting Information (SI) Table S1). Equation 2 shows the calculation of embodied GHG emissions.

$$\mathrm{EI}_m = \sum_{i=1}^{4} (\mathrm{EF}_{m,i} \times \mathrm{MS}_{m,i}) \tag{2}$$

Where $\mathrm{EI}_m$ is the total embodied GHG emissions for material $m$, summed for the four construction sectors $i$; $\mathrm{EF}_{m,i}$ is embodied GHG emission factor of construction material $m$ in construction sector $i$; and $\mathrm{MS}_{m,i}$ is the material stocks of type $m$ in construction sector $i$.

*2.1.3. Spatial and Socioeconomic Analysis.* ArcGIS 10.2 was used for spatial analysis. The city center of Beijing locates at 116.3968°E, 39.9247°N in Jingshan Park. We followed the ring belt roads of Beijing, setting the city center as circle center and 1km, 3 km, 7 km, 10 km, 13 km as radius, and then calculated the MS and densities in 0−1km, 1−3 km, 3−7 km, 7−10 km, and 10−13 km belts, respectively.

To facilitate the spatial analysis of built environment stocks, GIS polygon data were geographically transformed to raster data in a fitted resolution (500 m × 500 m). In total, 6297 grids with material stocks were extracted out of 7360 grids (with 1063 blank grids). When reassigning the building typology (derived from land use as detailed in Section 2.2.1), we used the following principle: If over 50% of the building floor area in one grid was occupied by a certain building typology (e.g., residential buildings), this grid was entirely defined as that typology. Relations between building material stock, building floor area ratio (building's total floor area to the size of land upon which it is built), average number of floors (the total number of floors of a building to the number of buildings in each grid), and road material stocks were then analyzed and plotted.

Spatially refined population and economic data, both in 500m × 500 m grids, were used to further reveal more in-depth implications and socioeconomic drivers (population and GDP) behind urban built environment stocks growth. Population density and population data in Beijing in 2018 were acquired from WorldPop Mainland China data set.[51] GDP density data were generated based on total GDP and a disaggregation method as reported in the literature.[52]

**2.2. Data Collection and Processing.** The geographical location and footprint information on in total 295 896 buildings in Beijing were obtained from AutoNavi Company (https://www.amap.com/). Due to gaps in the original data, this data set appeared as a large rectangle area from 116.1605°E, 39.7649°N to 116.5701°E, 40.0413°N. This adds up to an area of 1064 $km^2$, covering 77% of the land area of Beijing's six core functioning and developing districts (Dongcheng, Xicheng, Haidian, Chaoyang, Fengtai, Shijingshan). Despite an obvious underestimation due to such a gap, we deem this represents the majority of population, economy, and in particular core built-up area of Beijing and is thus sufficient for our purpose.

Similarly, spatial distribution data on infrastructure (road, railway, and metro) were obtained from AutoNavi Company in 2018. The road networks include all types of 273 917 roads (from expressway to the first, second, third, and fourth class roads) with name, location, type, starting-ending points, length, and width. 766 single-track railways, and 22 metro lines with 354 stations were also included.

*2.2.1. Deriving Building Attributes Based on Big Data Mining and Analytics.* While location and number of floors of buildings are readily available from AutoNavi, building typology and age attributes are not available there and have to be derived using other methods.

- For building typology: We used the latest (year 2017) Beijing land use data in a 30 m × 30 m resolution with 12 detailed types (commercial, municipal, storage, industrial, public, historical, educational, residential, sport, parking, agricultural, and other mixed-use buildings) obtained from the planning administration of Beijing (see SI Figure S1) and a spatial overlap analysis in ArcGIS to assign each building a typology attribute (see in the SI Table S2).
- For the age of buildings: We analyzed the central points of building footprints and matched them with the nearest residential/commercial point of interest (POI) data to assign each building a POI information. Then, building age and corresponding location information


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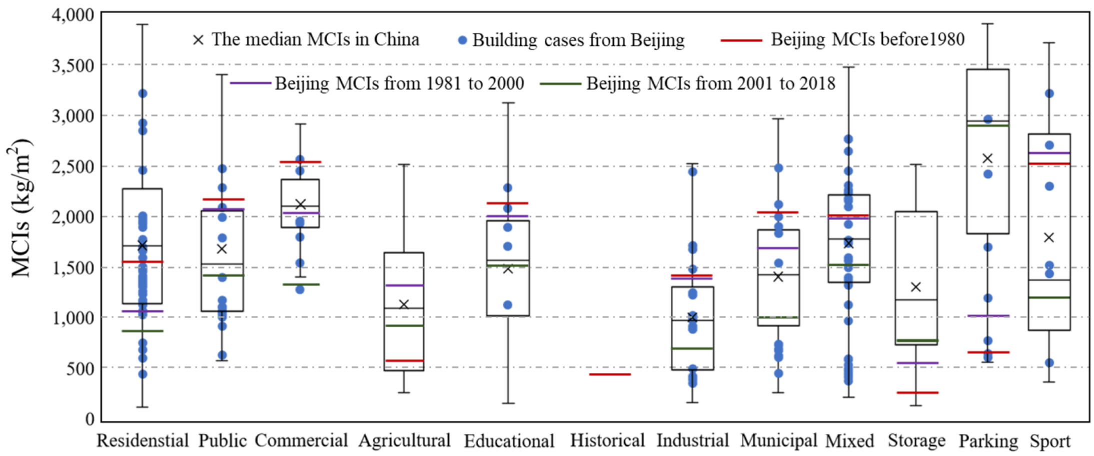


**Figure 2.** MCIs (kg/m$^2$) used for the 12 building typologies in Beijing. The box-plot represents the national data; the blue spots are the cases in Beijing; and the red, purple, and green lines represent Beijing's building MCIs for pre-1980, 1981 to 2000, and 2001−2018, respectively.

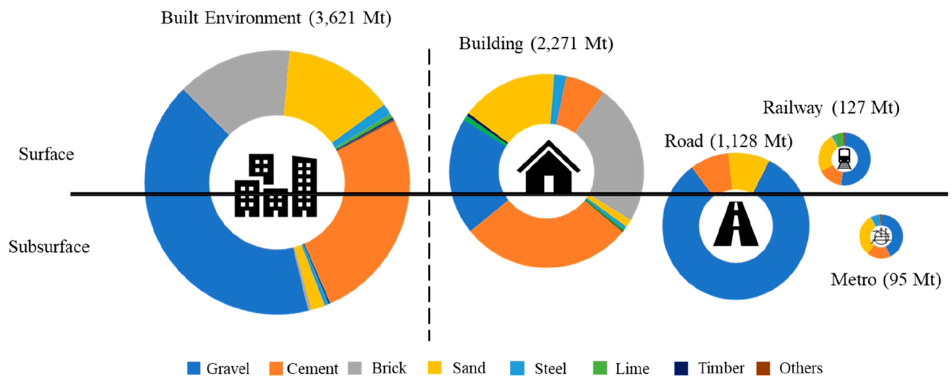


**Figure 3.** Quantity and composition of urban built environment stocks in 2018 in Beijing by typology and by material. The solid line distinguishes surface (above line) and subsurface (below line) built environment stocks and the circle size is proportional to real values.

were collected from the largest real-estate agency Web site in China (SouFun, http://soufun.com/) using a web-crawling approach. Using the collected location information, we searched the nearest surrounding POI and derived the age information for 93% of buildings. A K-nearest neighbors algorithm (KNN) method was used to supplement the 7% missing information (see in the SI Table S3 and S4). We used 10-fold cross-validation in labeled data and calculated the overall accuracy of year of construction information as 92%, which is good enough to meet the minimum standard of 85% proposed by the United States Geological Survey.[53] The data collection, description, and application were detailed in SI Table S5.

*2.2.2. Compiling a Building Material Composition Database for Beijing and China.* We compiled building MCIs data set for Beijing and China from various sources including construction bill of quantities (from construction companies and archives), expert interviews, and literature (reports, books, and journal articles). In total, the material inventories of over 1800 building samples (including subsurface components such as basement, underground garage, and foundation) constructed between 1963 and 2017 were collected, of which over 100 are the cases in Beijing. These building samples were further classified into 12 building typologies in accordance with the building design codes in China, and three construction age cohorts (pre-1980, 1981−2000, and 2001−2018) based on the observation of the change of Chinese building lifetime[54] and differences in MCIs (see Figure 2). We used the average of MCIs of building samples in Beijing whenever possible, but when samples are less than 10, the average of MCIs of an area with similar climate and architecture characteristics was used as a proxy instead. MCIs of historical buildings (mainly wood structure) were referred to a Japanese study[17] due to data gaps.

For infrastructure, road MCIs were taken from material inventories of real construction cases in five different typologies. Railway MCI data were extracted from a study on material stock analysis of high-speed rail in China using national level data.[14] Metro MCI data were based on inventories provided by Beijing Mass Transit Railway Operation Corporation Limited (see SI Table S6a−g).

## 3. RESULTS AND DISCUSSION

**3.1. The Quantity, Composition, and Age of Built Environment Stocks in Beijing in 2018.** Figure 3 illustrates the quantity and composition of urban built environment stocks in 2018 in Beijing. The total material stocks reached 3621 Mt (140 ton/cap) in 2018, in which buildings contributed the most (62.7%), followed by road (31.1%), railway (3.5%), and metro (2.6%). With regard to building material stocks among different typologies, roughly half was found in residential buildings (1188 Mt, 52.3%), followed by commercial buildings (385 Mt, 17.0%), public buildings (208 Mt, 9.1%), and educational buildings (182 Mt, 8.0%) (see SI Figure S2). The nonmetallic mineral materials (96.8%)


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Table 1. Built Environment Stocks and Proportions in Different Belts from City Center in Beijing

| belt | total material stocks (Mt) | density (t/m$^2$) | building | road | metro | railway |
|---|---|---|---|---|---|---|
| 0−1km | 4.51 | 1.44 | 88.38% | 11.21% | 0.41% | 0% |
| 1−3km | 97.91 | 3.90 | 91.54% | 7.76% | 0.70% | 0% |
| 3−7km | 629.97 | 5.01 | 91.56% | 7.16% | 0.43% | 0.84% |
| 7−10km | 660.19 | 4.12 | 90.44% | 8.08% | 0.51% | 0.97% |
| 10−13km | 516.56 | 2.38 | 85.74% | 10.06% | 0.85% | 3.34% |

dominate the material stocks, represented mainly by gravel (1445 Mt), cement (1008 Mt), brick (529 Mt), and sand (523 Mt). This reflects the fact that urban construction required considerable amount of concrete (constituted of cement, gravel, and sand) and bricks.[19] Biomass and metallic materials together constitute a very small share (3.2%), in which timber (11 Mt) and steel (68 Mt) are the major types (See SI Figure S3).

Age wise, it is noticeable that almost 80% of building material stocks were found in buildings constructed or reconstructed during the 1990s (826 Mt, 36.4%) and 2000s (1050 Mt, 46.2%), while only around 10% was in buildings built before 1990 (see SI Table S7 and Figure S4). This can be explained by the fact that (a) MCIs of historical buildings are lower than other typologies of more recent buildings; (b) Buildings constructed quickly in the 1980s in China have shorter lifetime due to the increasing housing demand after the market economy reform and comparably lower quality control;[55,54] and (c) Beijing experienced a construction boom before the 2008 Summer Olympics (which was accompanied by a rapid population increase from 13.6 million in 2000 to 21.5 million in 2018 as well[47]).

Our results show that subsurface material stocks underground are significant. In Beijing in 2018, 1786 Mt (49.3% of total) of materials were stocked subsurface, similarly to result of Wakayama City center (47%).[17] The majority of subsurface material stocks located in buildings (788 Mt in total, including 130 Mt in foundation, 327 Mt in basement, and 331 Mt in underground garage, accounting for over one-third of the total building material stocks), roads (902 Mt), and metro (95 Mt). This high amount of subsurface construction material stocks indicate a necessity to address the materials accumulated underground in a truly circular economy.

The level of per capita built environment stocks of Beijing is slightly higher than those reported cities in developing countries (e.g., Shanghai,[30] Ezhou,[42] and Chiclayo[21]), but are overall lower than those in cities in industrialized countries (e.g., Wakayama city center,[17] Vienna,[19] and Padua[56]). This indicates the different levels of socioeconomic and population development of different cities. However, Beijing has higher stock density on a per-km$^2$ level comparing to other cities (including Salford Quays[17] and Melbourne[22]) excepted for Philadelphia,[24] due mainly to its limited land resource (so sacrificing skylines for land). Unfortunately, the inconsistent calculation method and system boundary hamper a more in-depth comparison (see more comparisons in the SI Table S8).

The stock results presented here, unavoidably, bear some uncertainties due to data gaps.

- First, as explained in Section 2.2, while we have a full coverage for roads, railways, and subways within the entire Beijing, the available building footprint data were, unfortunately, incomplete as a rectangle for the core parts of Beijing. This consequently leads to an underestimation of the total built environment stocks in Beijing, which can be improved by improving the building footprint data coverage in the future.
- Second, our building MCIs are based on 1800 building samples constructed from 1963 to 2017. Despite our best efforts, the size and representativeness of samples may lead to uncertainty in building MCIs as well. Developing robust and accurate MCIs databases is a time and labor-intensive task. Such bottom-up work and sole reliance on building and construction documents can be alleviated and complemented by using new types of data. For example, the increasingly available Building Information Modeling (BIM) information onfers a unified model and records for all actions and transactions in a design or construction process and has already been used for information integration, construction, and operation of buildings,[57] as well as urban mining studies.[58,59]
- Third, the big data mining and analytics used for deriving building typology information may not be the most accurate, because the land use data applied for matching building typologies is only in 30 m × 30 m resolution. And limited samples in SouFun Web site and the accuracy of POI used could also influence the precision of derived building age information.

### 3.2. The Spatial Distribution of Built Environment Stocks in Beijing.

Our integrated method enables a spatial representation of built environment stocks in Beijing (shown in Figure 3 and detailed in SI Figure S5−S9). Table 1 and SI Figure S10 represent the material stocks distribution in different belts from city center. Specifically, the center area (0−1 km), owing to the regulation on historic buildings/monuments protection, represents relatively lower stock intensity (4.5 Mt and 1.4 t/m$^2$). And the densest area is found in the 3−7 km belt with 630 Mt and 5.0 t/m$^2$, and the 3−10 km belts together contained almost half (49.1%) of total material stocks. The suburb areas within 10−13 km (516 Mt and 2.4 t/m$^2$) witness outward development and fast growth after saturation of stock density in more central areas.

The built environment stocks in 500 m × 500 m grids (visualized as both grid and elevation maps in Figure 4) indicate that the less dense grids locate in both central and outer parts of Beijing. These central grids or clusters with low values represent basically those historical or protected blocks since Beijing has a history of over 3000 years as a city and over 600 years as the capital of China. This is different from other Chinese megacities like Shanghai,[30] Taipei,[25] Guangzhou,[33] Hangzhou[33] or Suzhou,[33] where the densest areas are normally found in the center.

Typology or urban function wise, commercial grids have the highest material stocks density (7.96 t/m$^2$) in Beijing, followed by residential (4.94 t/m$^2$), public (3.39 t/m$^2$), and educational (2.6 t/m$^2$) grids. The densest grid with 3274 kt and 13.1 t/m$^2$ M is found in the central business district (CBD) of Beijing. The builidng material stock densities of indutrial (1.24 t/m$^2$),


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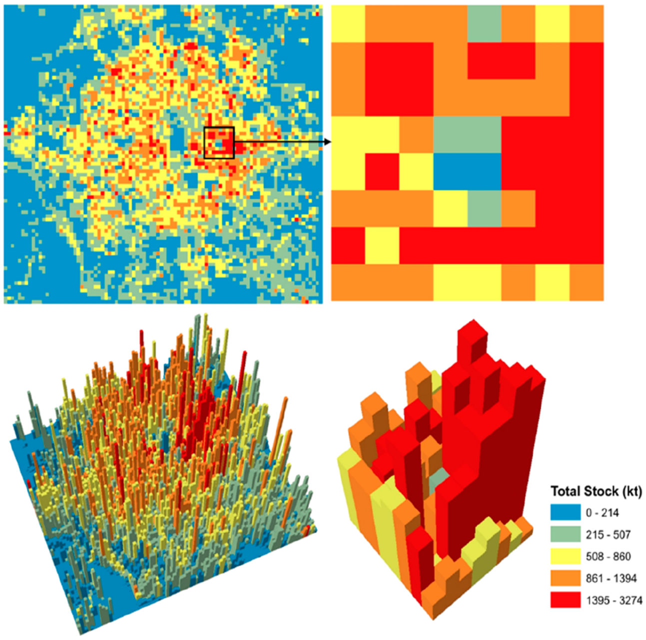


**Figure 4.** Built environment stocks of Beijing (left column) and selected area (right column) in 500 m × 500 m grids, both as heat maps (top row) and elevation models (bottom row).

agricultural (1.19 t/m$^2$), sport (0.9 t/m$^2$), storage (0.85t/m$^2$), and parking (0.57 t/m$^2$) grids are relatively lower. For comparison and a closer look, we selected and visualized nine sites of threetypical building typologies (residential, commercial, and educational) in the SI Figure S11.

Figure 5a and b suggest that total building height (measured by the total number of floors in each grid) and the average building height (measured by the total number of floors divided by the number of buildings in each grid) correlate well with building material stocks. In other words, stocks in denser area may have sprouted dozens of skyscrapers, and Beijing is sacrificing skylines for space. Additionally, as shown in Figure 5c, the correlation between material stocks and the building compactness (measured by floor area ratio, that is, the floor area divide by grid area) notably implies that stock in denser area (mainly commercial area) can provide more humane working and living space in buildings, suggesting the importance of urban planning to avoid overconcentration of stocks during urban sprawl.

The correlation between transport infrastructure stocks and building material stocks is not high, suggesting lower road network density (which contributes significantly to the total infrastructure stocks) in Beijing comparing to other megacities (e.g., New York, London, and Chicago)[60] and buildings are scare in transportation hubs (Figure 5d). Moreover, more than 80% of the most stock intensive grids for road materials (over 2 t/m$^2$) locate in grids with lower building material stocks (less than 2 t/m$^2$), revealing the inverse relationship between building and road stock densities, which was also found in an earlier German case study.[61]

**3.3. Implications of the High-Resolution Mapping of Built Environment Stocks on Urban Sustainability.** The high-resolution mapping of urban built environment stocks can facilitate the exploration of urban resource and environmental strategies and socioeconomic drivers on a more refined level. For example, the mapping of built environment material stocks in Beijing can (i) inform decision makers about where certain materials in what quantities are likely to be replaced and recycled; (ii) allow for an estimation of the overall material requirements needed for building new cities in the future, especially for cities in China and other developing countries;

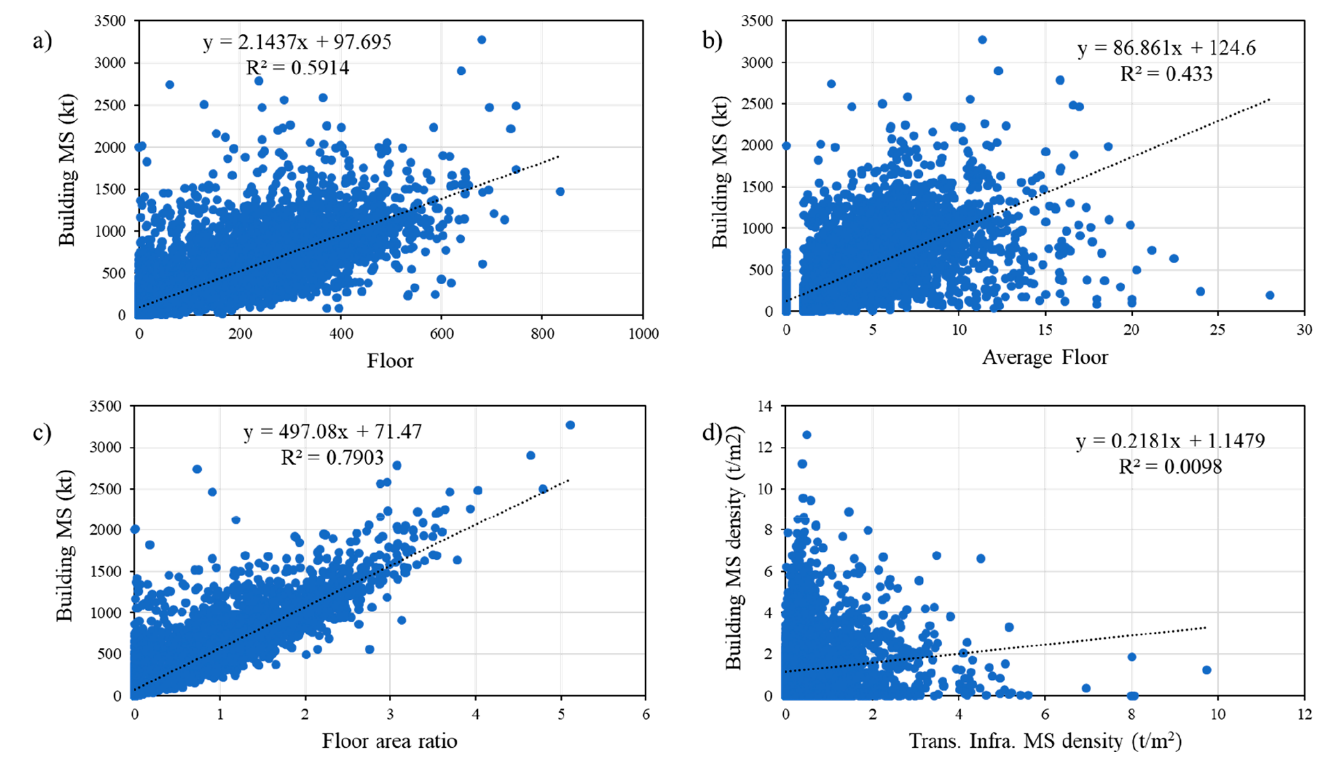


**Figure 5.** Correlation between building material stocks (MS) and floors, floor area ratio, and transport infrastructure material stocks in Beijing.


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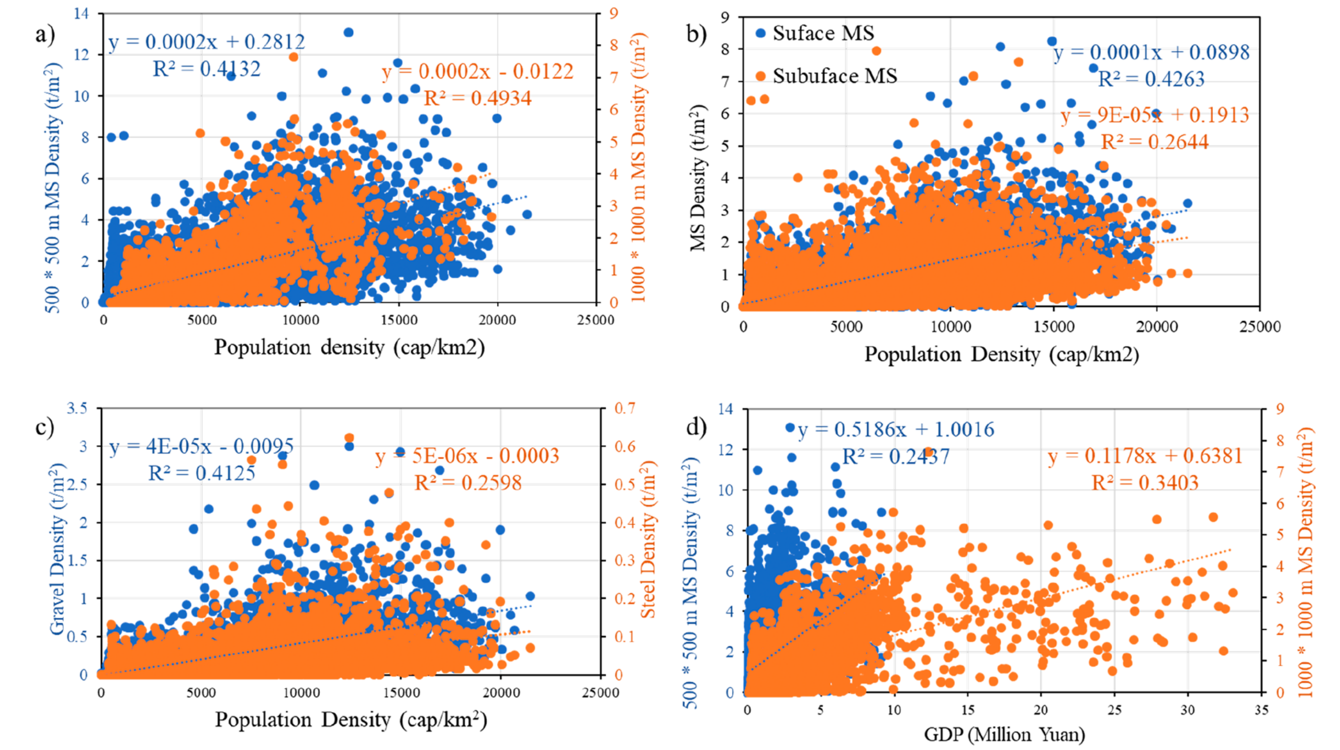


**Figure 6.** Correlation between built environment stocks and socioeconomic factors in Beijing.

and (iii) enable the exploration of the role of urban form in city weight growth and urban sustainability transition.

As shown in Figure 6a, city compactness (measured by population density) correlates well with material service capacity (measured by material stock density), particularly in larger spatial grids ($R^2$ = 0.41 at a 500 m × 500 m resolution, $R^2$ = 0.49 at a 1000 m × 1000 m resolution, and $R^2$ = 0.69 at a 2000 m × 2000 m resolution, see in the SI Figure S12). Aboveground material stocks correlate better with human activities than subsurface stocks, because the underground buildings, roads, and metros offer no or very little working and living space (Figure 6b). Among different construction materials, sand and gravel correlate better with population density than cement, steel, and brick, due to the wide use of mineral construction aggregates (gravel and sand) in the built environment (see Figure 6c and SI Figures S13−S15).

The built environment stocks correlate very weakly with GDP at a 500 m × 500 m resolution and slightly better in larger grids (1000 m × 1000 m) (Figure 6d), in contrast to their strong correlation at the city level.[62,63] A disaggregated more detailed analysis shows that there is no correlation between the stock densities and primary and secondary industry GDP at the grid level, while a closer relationship is found for the tertiary industry GDP. This may reflect the service oriented economy of Beijing as a center of political, economic, and cultural activities in China and consequently scattered distribution of agriculture land and industry activities (e.g., many polluting industry was moved out via the 2013−2017 Clean Air Action Plan[64]) (see SI Figure S16−S18). As Beijing continues to mature in urban development and lower its reliance on the construction sector in economy development, the decoupling effect between stock and GDP is worth further exploring (not possible in the present analysis due to lack of temporal data for stocks).

C&D waste is becoming a pressing risk threatening sustainable urban development in China, particularly considering that the building lifetime is mostly less than 40 years (even less than 30 years for building built in the 1980s and 1990s).[54] From a resource and waste management perspective, our spatially refined characterization of construction material stocks in Beijing could allow for forecasting of the amount, composition, and value of C&D waste. Since most of the C&D waste is still illegally dumped or landfilled in China,[65] potential improvements to promote the C&D waste management, guided by the circular economy principle,[61] are urgent and necessary, for example by increasing the recycling rate (currently less than 5%[62]) of construction materials. In particular, with an unprecedented boom of building construction and renovation in China[66] and the expanding of residential built-up areas (more rapidly than the other typologies[67]), residential buildings should be given a special focus.

The total embodied GHG emissions in Beijing's built environment stocks reached 1141 Mt of $CO_{2\text{-eq}}$ (87% in buildings), accounting for 11.5% of the total carbon emissions of China in 2018.[68] Construction of residential (49%) and commercial buildings (16%) created staggering climate impacts due to the use of three key construction materials (69.1% from cement, 15.8% from steel, and 12.5% from brick) (see Figure 7). For cement and steel, the most intensive census block groups (orange and red color in Figure 7b and c) contain 12% of total building material stocks whereas over 25% of embodied GHG emissions due to their energy intensive production. Bricks embodied GHG emissions are more widely distributed across the urban area especially in the southeast corner (Figure 7d). The embodied GHG emissions of cement alone represent 791 Mt $CO_{2\text{-eq}}$, which is equivalent to almost 6 years of electricity demand of Beijing in 2018 (based on an electricity consumption of 114 238 GWh[69]).


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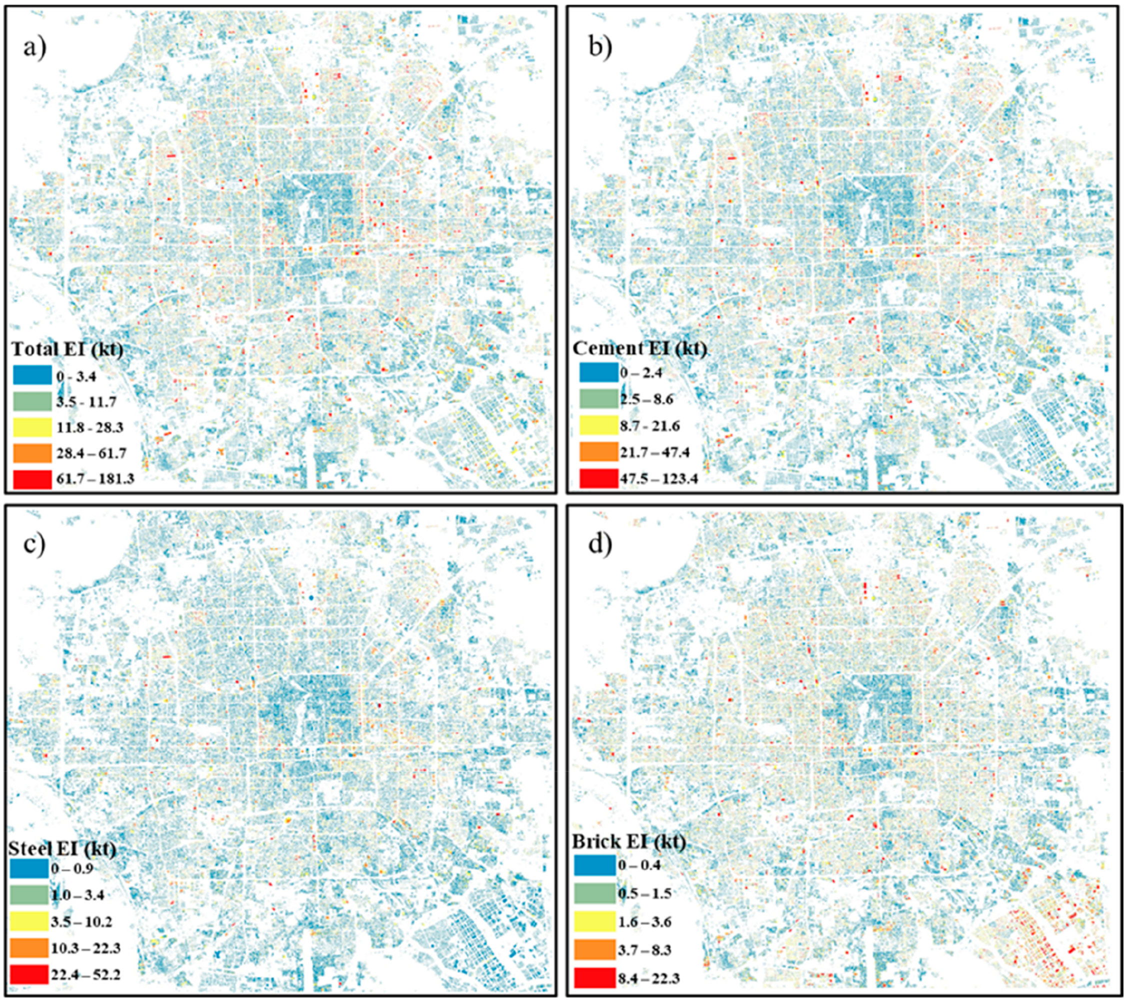


**Figure 7.** Spatial distribution of embodied GHG emissions (EI) in 2018 in Beijing in (a) total construction material stocks, (b) cement stocks, (c) steel stocks, and (d) brick stocks.

The Nobel Prize laureate in economics Joseph E. Stiglitz assessed China's urbanization as one of the two most fundamental global changes in the twenty-first century.[70] With a high speed of urbanization in the past decades (1.3% annually), the share of people living in urban areas rose from 17.9% in 1978 to 58.5% in 2017, and will increase to 60% (over 830 million) in 2020.[71] Consequently, continued construction of buildings and transportation infrastructure will inevitably increase demand of raw materials[72] and generation of waste and emissions. If the material stock density in Beijing's 7−13 km belt was to be developed to the level of the 3−7 km belt, built environment stocks and $CO_2$ emissions from primary materials use would increase by 713 Mt and 225 Mt, respectively, and this $CO_2$ emission is about 10 times higher than the embodied $CO_2$ emissions of building stocks in Melbourne, Australia.[22] Assuming the correlation obtained from our case of Beijing (Figure 5a) is applicable to all Chinese cities, and that the urban built-up area remains the same as in 2017 (56 225 $km^2$),[73] at least 169 gigaton (Gt) of construction materials would have been stocked in China's urban built environment by 2020 (the target year of China's New-Type Urbanization Plan), equaling to 53 Gt of embodied GHG emissions (or over 5 times the present annual carbon emissions of China[68]).

To address these increasing challenges of "embodied carbon",[74] a holistic and systems approach would be needed. For example, a reduction of material use would be most effectively achieved through recycling C&D waste and prolonging the service lifetime of buildings and infrastructure (strengthening quality and maintenance). Moreover, relationships between material stocks, building height and typologies, and the socioeconomic factors and the inverse relationship between building and transportation infrastructure stock density all highlight the importance of spatial planning in reducing urban resource use and environmental impacts. This perspective remains poorly understood and deserves further analysis as more built environment stock studies at a high resolution become available.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b07229.

Detailed description of the system definition, analytical solutions to the system, and data sources (PDF)

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### Notes

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