Mapping nationwide material stock turnover: high-resolution spatial analysis of building material stock and flow patterns across Japan 2003–2020

Nagata, S.; Hasegawa, M.; Fishman, T.; Shirakawa, H.; Tanikawa, H.

DOI: 10.1111/jiec.70100

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH ARTICLE

Mapping nationwide material stock turnover

High-resolution spatial analysis of building material stock and flow patterns across Japan 2003–2020

Sota Nagata[1] | Masatoshi Hasegawa[1] | Tomer Fishman[2] | Hiroaki Shirakawa[1] | Hiroki Tanikawa[1]

[1]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

[2]Institute of Environmental Sciences (CML), Faculty of Science, Leiden University, Leiden, The Netherlands

Correspondence
Sota Nagata, Graduate School of Environmental Studies, Nagoya University, D2-1(501), Furo-cho, Chikusa-ku, Nagoya 464–8603, Japan. Email: nagata.sota.k5@s.mail.nagoya-u.ac.jp

Editor Managing Review: Stefan Pauliuk.

Funding information
European Research Council, Grant/Award Number: 101116116; Japan Science and Technology Agency, Grant/Award Number: JPMJPF2204; Environmental Restoration and Conservation Agency, Grant/Award Number: JPMEERF20231005; Japan Society for the Promotion of Science, Grant/Award Numbers: JP23H00531, JP24K03140, JP25H01206; Ministry of Education, Culture, Sports, Science and Technology, Grant/Award Number: JPJ010039

Abstract

Understanding the dynamics of building material stocks and flows, including the turnover processes of building stock, is important for promoting sustainable resource use in cities. This study provides high-resolution, integrated mapping of building material stocks and flows across various cities and regions in Japan, offering a detailed view of the country's spatial material metabolism. This research combines bottom-up estimates of material stocks and flows with spatial analysis using material metabolism indicators, examining how patterns of material stock turnover vary across Japan. Spatial variations in material stock turnover highlight regional factors that influence stock–flow dynamics and offer insights into local resource use and policy development tailored to specific regional contexts. In this study, the national stock turnover rate in 2020 is estimated to be 1.16%/year for inflow and 0.64%/year for outflow, with more active metabolism observed in the central areas of large metropolitan regions and lower levels in low-density rural areas. Additionally, distinct patterns of material metabolism were observed across districts, associated with redevelopment and urban sprawl. This study illustrates how spatially detailed approaches can support the analysis of stock–flow dynamics across the country and contribute to the development of sustainable resource use strategies tailored to local conditions.

KEYWORDS
built environment, industrial ecology, material stocks, material stock turnover rate, spatial analysis, urban metabolism

1 | INTRODUCTION

Resource use in urban buildings generates a range of environmental impacts through processes such as resource extraction, material production, and waste generation (Augiseau & Barles, 2017). Consequently, achieving circular resource use in the building sector has emerged as a critical challenge (Timm et al., 2023). Japan, which experienced rapid economic growth driven by mass production and consumption (CAA, 2020), is now striving to transition from a linear to a circular model of resource use (MOE, 2003). While recycling initiatives in the construction sector have improved recycling rates (MLITT, 2014a; MOE, 2021), substantial challenges remain in promoting the long-term efficient use of resources and realizing sustainable recycling practices. Structural issues related to the "turnover" of the building stock have become increasingly apparent in recent years.

Japan currently faces several structural issues related to the turnover of its building stock. Many buildings constructed during and after the period of rapid economic growth are now approaching the end of their service life, raising concerns about the increasing demolition waste (Fujikawa et al., 2006). Given the limited recycling options for construction waste, the scarcity of outlets for recycled materials has become a pressing issue (MLITT, 2014a; TMG, 2024). While the long-term use of existing building stock could be a promising means of reducing both new resource input and waste generation (MLITT, 2020a), the short lifespan of buildings has been a long-standing issue in Japan (Wuyts et al., 2019). In urban areas, many large-scale redevelopment projects are underway to enhance urban functionality (Cabinet Office, 2020). Meanwhile, in rural and regional areas, population decline has led to an increase in unutilized and vacant buildings, which may pose governance challenges if demolition is not properly managed (Wuyts et al., 2020).

To address these challenges, it is essential to develop a better understanding of building stock–flow dynamics. Urban metabolism research analyzes building resource use in terms of stocks and flows. Materials flow into cities as part of the built environment stock, provide services over time, and eventually become obsolete stock or construction waste. Consequently, stock–flow dynamics, along with the services they provide, play a pivotal role in shaping resource demand, waste generation, and overall environmental efficiency (Haberl et al., 2017; Müller, 2006). To date, stock dynamics modeling (Müller, 2006) and recent investigations into long-term, economy-wide or nationwide relationships among stock, flow, and service (Streeck et al., 2020; Tanikawa et al., 2021) have deepened our understanding of these interlinked systems. However, many of these studies have focused on national or macroeconomic scales, and it remains a challenge to understand the direct relationships between the urban metabolism of buildings and socioeconomic, spatial, and geographical factors, especially local ones (Kolkwitz et al., 2023; Lanau et al., 2019). Since buildings provide services in specific physical locations (Tanikawa et al., 2015), their potential for long-term use or timely replacement is contingent upon contextual spatial factors. Therefore, to understand the detailed process of material stock turnover and promote the effective utilization of buildings, it is crucial to examine the characteristics and drivers of building stock replacement within a regional context (Huuhka & Kolkwitz, 2021; Wuyts et al., 2020). Furthermore, a localized understanding of stock–flow dynamics is vital for advancing urban mining and construction waste management (Göswein et al., 2019; Guo et al., 2021; Lanau et al., 2019). For instance, the viable transportation distance for construction waste is relatively short—approximately 15 km in the case of concrete waste (MLITT, 2020b). Accordingly, the development of localized recycling systems necessitates a spatially detailed understanding of local stock–flow dynamics.

Several recent studies have successfully captured historical changes in building stocks and flows at high resolution by developing "4d-GIS" systems (Tanikawa & Hashimoto, 2009), which apply a bottom-up stock estimation method to time-series spatial building datasets (Chen et al., 2016; Guo et al., 2021; Miatto et al., 2019; Tanikawa & Hashimoto, 2009; Yang et al., 2023). Some studies have further extended their focus to explore building replacement, its driving forces, and the relationship between stocks and flows from the perspectives of urban planning and various geographic and spatial factors (Augiseau & Kim, 2021; Huuhka & Kolkwitz, 2021; Kolkwitz et al., 2023; Mao et al., 2022). However, most such analyses remain limited to individual cities or small regions. While recent stock mapping efforts have broadened their spatial coverage (Frantz et al., 2023; Haberl et al., 2021; Tanikawa et al., 2015), comprehensive spatial analyses that concurrently examine both stocks and flows across diverse socioeconomic contexts at broader regional scales remain scarce. To implement large-scale sustainable resource use strategies tailored to local conditions, it is necessary to gain a more detailed understanding of the material metabolism conditions specific to different regional contexts.

To address this gap, the present study spatially maps the relationship between building stocks and flows across all of Japan to provide high-resolution insights into the country's spatial urban metabolism processes, with a specific focus on stock turnover. Japan is one of the few countries where nationwide, high-resolution building data are available in time series. Therefore, a study in Japan serves as a valuable case for applying a 4d-GIS-based approach to nationwide building material stock and flow analysis. Notably, Japan is characterized by relatively short building lifespans compared to some other developed countries (MLITT, 2008) and faces numerous challenges related to building turnover. Our case study in Japan can thus serve as a valuable example for studying issues related to building turnover, and its insights may also be applicable to a wide range of countries and regions that are likely to face similar challenges in the future.

We conduct a nationwide spatial analysis of building stocks and flows from 2003 to 2020 using an updated time-series version of the stock database initially developed by Tanikawa et al. (2015). This update incorporates methods developed in previous studies (Asakuma et al., 2018; Ota et al., 2023) and enables simultaneous stock–flow analysis. Through this approach, we estimate stock turnover indicators across Japan at a 500 m × 500 m grid resolution. By spatially identifying the characteristics of stock turnover, this study provides insights into regional similarities and differences in stock and flow dynamics and the factors that cause such regional differences, offering fundamental knowledge for managing material flows and addressing local resource use issues.

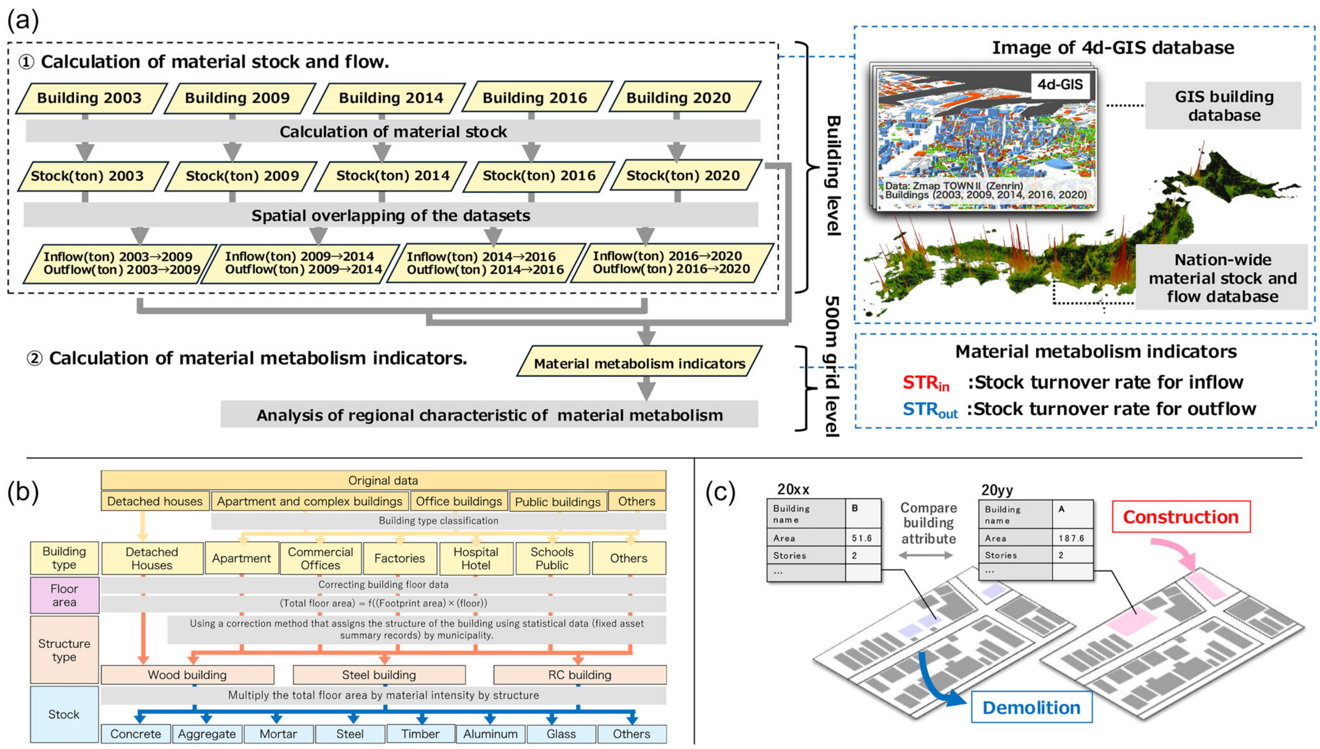

FIGURE 1 Research methods: (a) research framework; (b) calculation of material stock; and (c) calculation of material flow.

2 | METHODS

2.1 | Research flow

Figure 1 illustrates the overall research flow. This study employed an updated version of the methodology developed by Tanikawa et al. (2015) and Ota et al. (2023) to estimate building material stocks and flows based on building GIS datasets covering Japan. We used Zmap-TOWN II (ZENRIN CO., LTD., 2020), a detailed building footprint GIS dataset covering the entire country. The five years, 2003, 2009, 2014, 2016, and 2020, were selected for material stock estimation due to data being available only for these years. First, the material stock of each building was calculated. Then, by overlaying time-series datasets and linking buildings across different years, a 4d-GIS database was constructed. Material inflows and outflows were estimated by detecting building replacements between these years. Finally, these estimated stocks and flows were aggregated within fixed spatial units, and indicators representing material metabolism were calculated, enabling the analysis of material metabolism at a high spatial resolution.

2.2 | Calculation of material stock

We calculated material stock using Zmap-TOWN II (ZENRIN CO., LTD, 2020), which covers all buildings in Japan and contains information such as building names, usage types, and number of floors, as recorded by surveyors for each structure. In Zmap-TOWN II, primary buildings (excluding secondary structures) are categorized into five groups: public buildings, detached houses, office buildings, complex buildings (e.g., apartment complexes and tenant buildings), and buildings with missing information. For the purpose of precise material stock estimation, this classification was further refined. First, a list of keywords related to building names reflecting their functions was created, and building types were identified accordingly. A simplified version of this method was previously used by Ota et al. (2023), but in the present study, the keyword list has been expanded to enable more accurate classification. Second, for complex buildings, tenant data were used to refine classifications, enabling better differentiation between apartment and mixed-use office buildings. This approach is newly introduced in the present study. As a result, building types were ultimately classified into seven categories, aligned with Japan's statistical classifications (MIAC, 2020a): detached houses, apartment buildings, commercial and office buildings, factories, hospitals and hotels, schools and public buildings, and others. Details of this classification are provided in Section 1 of Supporting Information S1. Buildings with missing information—such as unknown or masked occupant data—were grouped into the "other" category. As in Tanikawa et al. (2015), minor attached buildings other than the main building, such as sheds, are excluded from the estimation due to the difficulty in identifying the building type.

After the building usage type classification, the calculation of material stock followed the method used in Tanikawa et al. (2015) and Ota et al. (2023). First, the building floor area was determined based on corrected calculations using building footprint and number of stories. Next, the structural type of each building was assigned based on municipality-level statistical data (MIAC, 2020a). Section 2 of Supporting Information S1 provides a detailed explanation of this method. Finally, the material stock of each building was calculated by multiplying its gross floor area by the material intensity, which varies depending on the building's structural type. We used the material intensity values from Tanikawa et al. (2014), as shown in Table S2 of Supporting Information S1.

2.3 | Calculation of material flows

In this study, material inflows and outflows were calculated from the construction and demolition activity, respectively, of the buildings in the intervals between the periods captured by the material stock GIS datasets, similar to previous 4d-GIS studies (Guo et al., 2021; Miatto et al., 2019; Tanikawa & Hashimoto, 2009). First, two consecutive datasets were spatially overlaid. Building pairs with the largest overlapping areas were identified as candidates for being the same building. Next, these pairs were compared based on their attributes to determine whether they were identical, indeed the same building. The identical buildings share attribute information and buildings that were not identical were classified as either newly constructed when only appearing in the latter dataset or demolished if only appearing in the earlier dataset. This process was automated using the methodology developed by Asakuma et al. (2018), Ota et al. (2023), and Bai et al. (2024). Section 4 of Supporting Information S1 provides detailed methods.

In certain districts (mainly rural), building construction and demolition were over-identified. This issue arises from older maps that did not cover all buildings in a location or described them only as simpler polygons. These buildings then appear in a newer map and get identified as new construction when in fact they already existed before. However, they are limited to certain municipalities because the original map data were created municipality by municipality, and accuracy issues often occurred at this level. Such municipalities, which comprise approximately 10% of the nation's municipalities, were excluded from the analysis. Most of these are located in mountainous areas, and the excluded buildings represent only 3% of the total on a floor area basis. Figure S3 of Supporting Information S1 shows the excluded municipalities.

2.4 | Framework for spatial analysis of stock turnover

To analyze regional stock and flow at high resolution, stock and flow quantities were aggregated into 500 m × 500 m grid cells, and indicators representing material metabolism were then calculated for each grid cell. Several previous studies have suggested and examined indicators of the relationships between stocks, flows, and service provisioning (Haberl et al., 2017; Hashimoto & Moriguchi, 2004; Tanikawa et al., 2021). Among these, the stock retention time (SRT) and the stock turnover rate (STR) directly relate stocks and flows. SRT is defined as the stock divided by the flow, indicating the mean residence time when an economy has a stable stock level (Tanikawa et al., 2021). Its inverse, STR, is defined as the flow divided by the stock. By scaling the flows to the size of their stocks, STR provides a normalized indicator of flows per unit of stock that can be compared across time and locations. In this study, we use this indicator in two versions: STR_{in}, which is the inflow divided by stock, and STR_{out}, which is the outflow divided by stock (Equations 1 and 2). These two equations together describe the relative metabolic rates of a location, helping to understand the turnover of materials. Their unit of measurement is %/year.

$$STR_{in} \equiv \frac{\text{Inflow}}{\text{Stock}} \tag{1}$$

$$STR_{out} \equiv \frac{\text{Outflow}}{\text{Stock}} \tag{2}$$

STR_{in} measures the speed at which new materials are supplied, in relation to the current stock base. It represents the proportion of new material inputs required each year, reflecting factors such as population or household changes, and the deterioration or obsolescence of existing stock. During a growth phase of the region, STR_{in} reflects the rate of stock expansion, whereas in a declining phase, it approaches zero as the demand for new construction diminishes. In a stable phase, it indicates the turnover rate of materials needed to maintain the region, as well as the average rate of depreciation and obsolescence of existing stock. When aggregated over time, STR_{in} represents the share of new stock in the existing total, indicating the overall "newness" of the stock in that region.

In contrast, STR_{out} shows the speed at which material stock is removed relative to the total stock. It reflects the annual share of buildings lost, which is the result of complete building obsolescence caused by factors such as aging or changes in societal needs (Wuyts et al., 2019). In

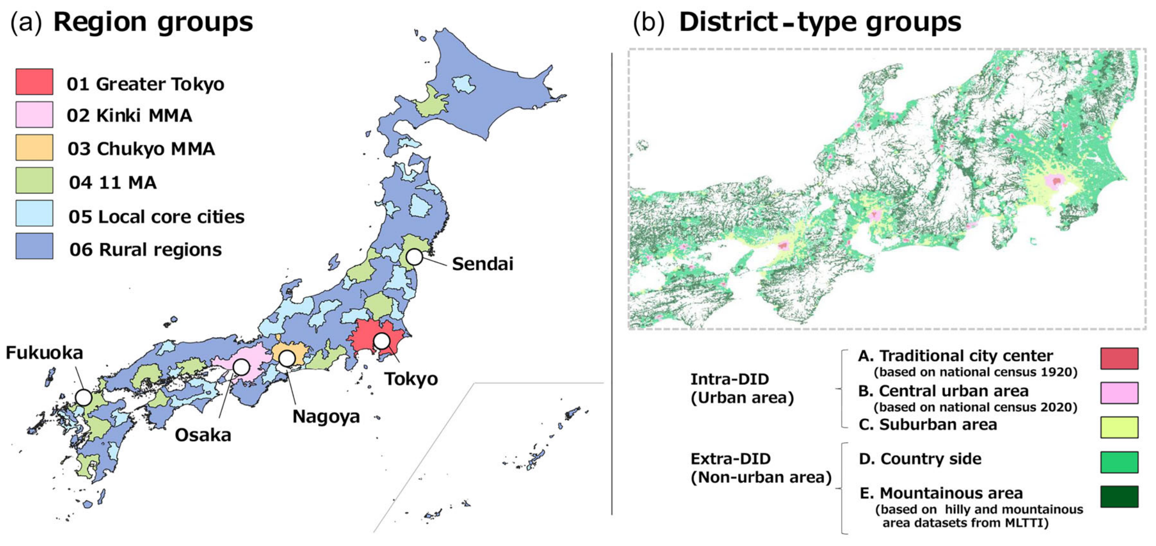

FIGURE 2 Framework for interregional comparisons: (a) regional groups and (b) district-type groups.

high-pressure development areas, the amount of physically removed stock may align with the volume of fully obsolete buildings. In other areas, stock that has lost its value or remains unused may persist without being demolished. Thus, STR_{out} does not always represent the building obsolescence rate. A high STR_{out} value suggests significant physical loss of stock and a high rate of waste generation.

2.5 | Regional classification

To compare stock turnover across socioeconomically distinct areas, we categorized Japan into six regional groups based on the definitions of mega metropolitan areas (MMA) and metropolitan areas (MA) from MIAC (2020b), core cities from MIAC (2023), and urban employment zones from CSIS (2015): the three major metropolitan areas ("Greater Tokyo," "Kinki MMA," and "Chukyo MMA"), other metropolitan areas ("11 MA"), core cities and their employment zones ("Core Cities"), and all remaining areas ("Rural Regions"), as mapped in Figure 2a.

Additionally, the 500 m × 500 m grid cells were classified into one of the five district types as mapped in Figure 2b. Using densely inhabited districts (DID) (MLITT, 2024), areas were categorized into urban and non-urban zones. Urban areas were subdivided into: traditional city centers, other parts of central city of the region (central urban area), and suburban areas. Non-urban areas were divided into countryside and mountainous areas. In rural regions, all urban areas were treated as suburban due to the lack of defined central cities. Classification used GIS data from MLITT (2015, 2016, 2020c).

3 | RESULTS

3.1 | Nationwide results

Figure 3 shows the material stock, inflow, outflow, and calculated STRs for each regions. Material stock levels across Japan's regions have been gradually increasing between 2003 and 2020. However, the growth rate has been declining; inflows have decreased over this period, indicating that stock growth in Japan is slowing down. The value of inflows is approximately twice that of outflows. This finding suggests that roughly half of the resource input contributes to stock growth, while the other half is used for stock replacement. This can be interpreted as simultaneous stock growth and replacement, with the amount of replacement being equivalent to the amount of growth.

The calculated STRs show a consistent national downward trend. STR_{in} declined from 2.72%/year (2003–2009) to 1.16%/year (2016–2020), while STR_{out} dropped from 1.30%/year to 0.64%/year over the same period. Regional variation in these metrics was limited; only Greater Tokyo exhibited a slightly elevated STR_{in} in 2020, at 1.36%/year. Based on these STR values, the corresponding SRTs (calculated as the inverses of STRs) in 2020 were approximately 86 years for inflow and 155 years for outflow. This result is broadly consistent with the findings of a previous case study on Japanese housing, which estimated the inflow-side SRT to be approximately 80 years in 2017 (Yamashita et al., 2021).

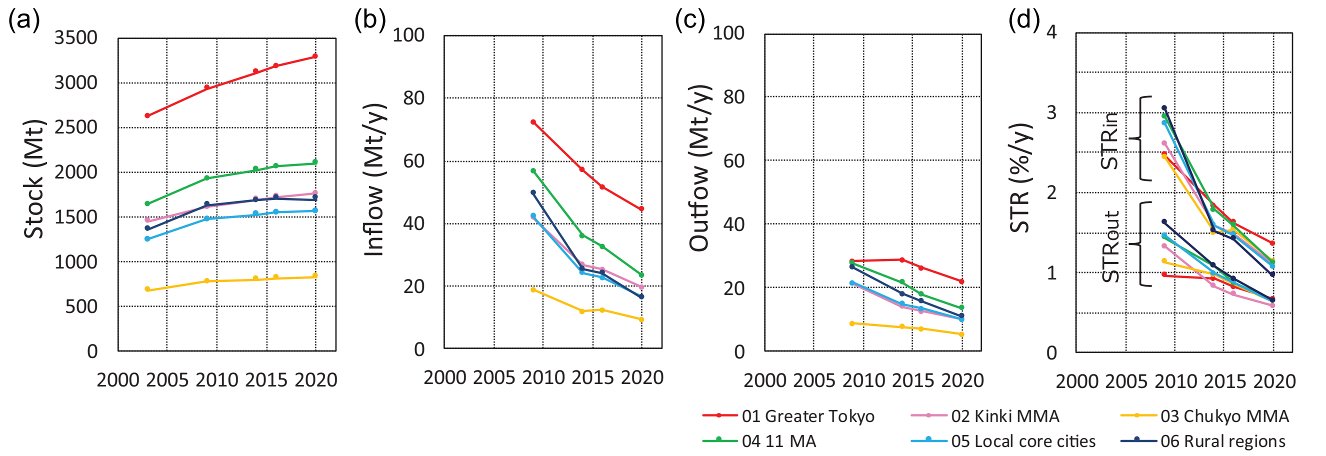

FIGURE 3 Estimated results of stock (a), inflow (b), outflow (c), and stock turnover rate (STR) (d) by regions. For inflow, outflow, and STR, the value at each time point represents the average from the previous data point to that time. Underlying data for this figure are available in sheet "Figure 3" of Supporting Information S2.

3.2 | Spatial distribution of stock turnover rate

Figure 4 shows the spatial distribution of STR_{in} values for the period 2009–2020, calculated as the 10-year average inflow per unit of stock in 2020, at 500 m × 500 m grid cells. The following analysis uses the 10-year average STRs.

Notably high STR_{in} values are observed in the coastal areas of Tohoku (Figure 4b) and along the Tsukuba Express corridor in the suburbs of Tokyo (Figure 4c,d). In Tohoku, the 2011 earthquake and tsunami caused widespread building collapse, followed by major reconstruction and urban redevelopment efforts, particularly through 2020 (Reconstruction Agency, 2025). The Tsukuba Express is a railway line that opened in 2005 as part of an integrated initiative to promote residential land development and new railway infrastructure in Tokyo's suburban areas (NILIM, 2015). The results of the STR mapping confirm that areas undergoing urban expansion or redevelopment tend to exhibit higher rates of material turnover.

Figure 4 also suggests that STR_{in} tends to show higher values in urban areas. For example, in the Tokyo metropolitan area (Figure 4c), there is a trend of higher STR_{in} values toward the city center (e.g., around 20% per 10 years). This suggests that in urban centers, where buildings are densely concentrated and stock density is high, turnover is also more active. In contrast, in mountainous and rural areas, many regions exhibit STR_{in} values ranging from 0% to about 5% per 10 years, which is relatively low. This implies that in rural areas, turnover tends to stagnate. These observations are analyzed in more detail in the following section.

3.3 | Urban–rural variation in turnover rates

To further focus on the differences in STR distribution across regions with varying economic conditions, a regional comparison of STR was conducted. Figure 5a shows histograms of the aggregated amount of stock by region, in which the bins are differentiated by STR values. These histograms describe how much of the stock in a region has high versus low turnover. In rural areas, a large portion of the building stock exhibits low turnover, with the distribution heavily skewed toward areas with STRs below 5% per 10 years. In contrast, urban areas contain substantial stock in both high and low STR zones, as illustrated by the bimodal distribution of stock in the Greater Tokyo region.

Figure 5b presents the first quartile (Q1), median, and third quartile (Q3) of STR_{in} and STR_{out} across grid cells for each regional and district classification. STRs are consistently higher in areas closer to urban centers. STR_{in}, especially, tends to be higher in larger economic zones, even within the same district type. These results suggest that turnover rates are generally higher in more urban and central areas, reflecting more active material metabolism in economically vibrant regions. Conversely, over 50% of the mountainous area grids show no turnover. These findings underscore a clear relationship between economic vitality and active material metabolism. All other estimated values of stock, flow, and STRs for each region and district group across all target years are summarized in the sheet "Calculation results by regions" of Supporting Information S2.

3.4 | District-level patterns in material metabolism

Figure 6 presents a map that characterizes the composite differences in regional material metabolism patterns combining both STR_{in} and STR_{out}. In this map, each grid cell is classified into one of the four groups based on whether their STR_{in} and STR_{out} values are above or below the national

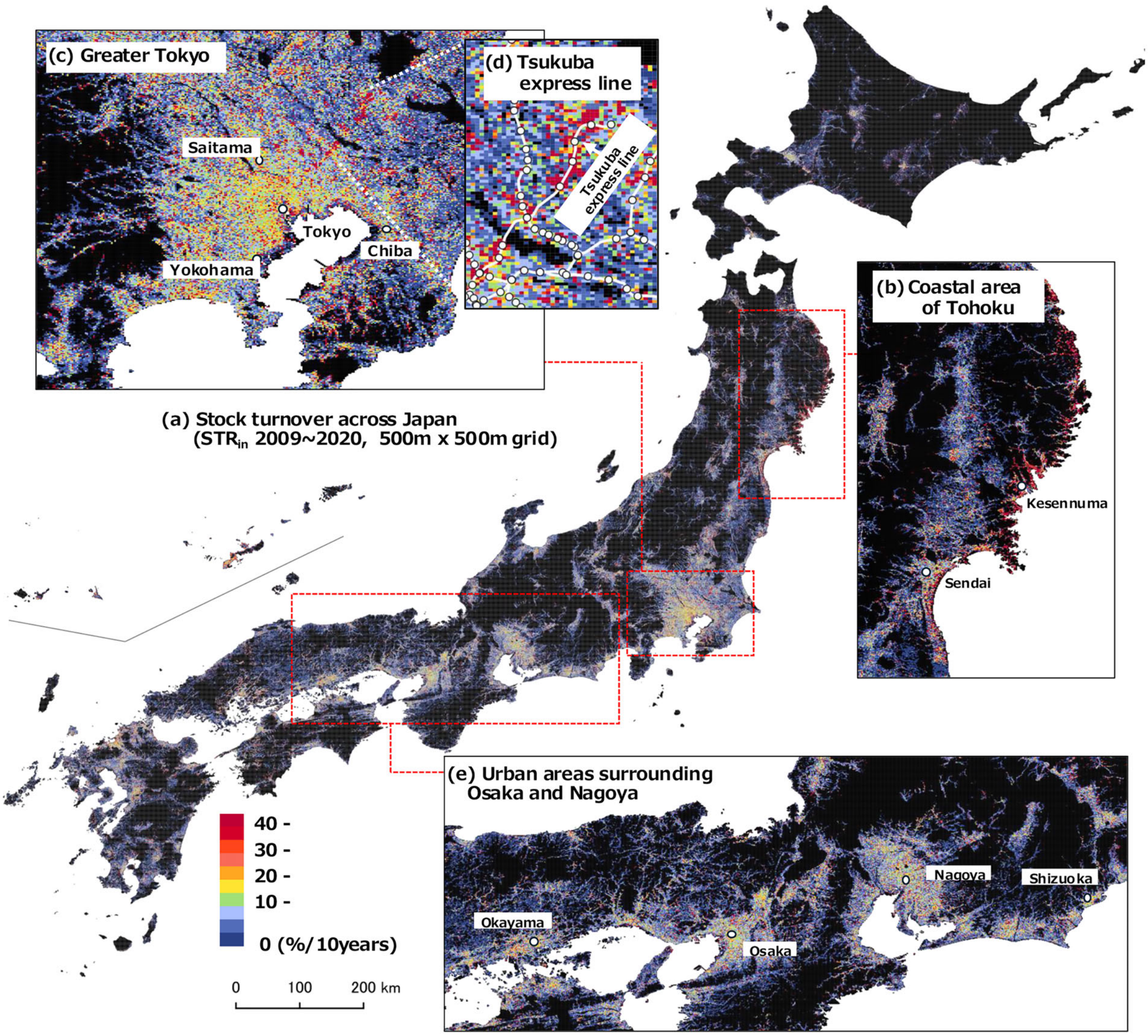

FIGURE 4 Calculated stock turnover distribution across Japan (a), with enlarged views of the coastal area of Tohoku (b), Greater Tokyo (c), the area around the Tsukuba Express Line (d), and urban areas surrounding Osaka and Nagoya (e).

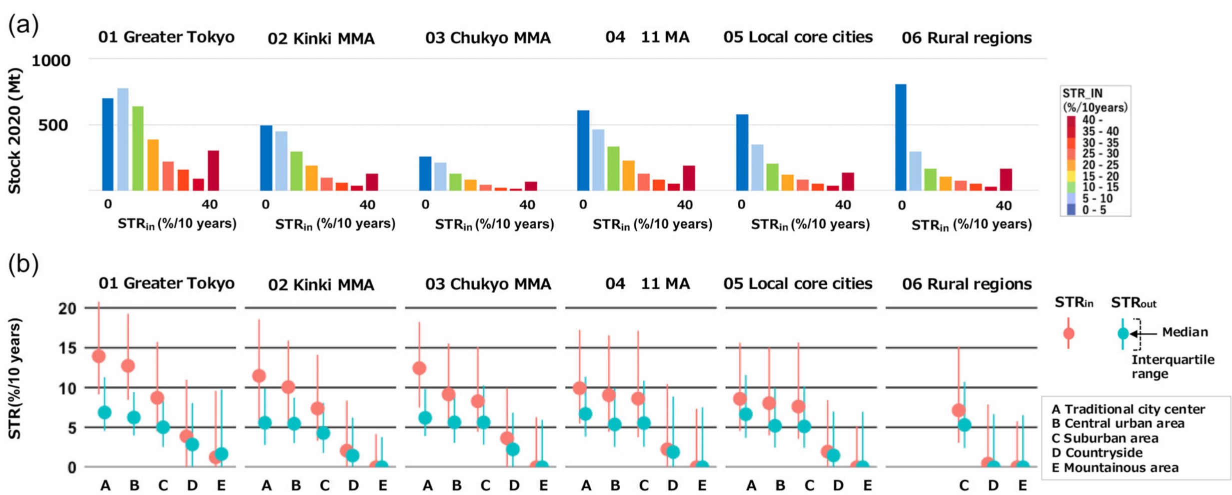

FIGURE 5 Spatial variation in stock turnover rates across urban and rural areas: (a) distribution of stock volume by stock turnover rate (STR) bins; and (b) statistical values (median and interquartile range) of grid-level STRs by regional groups and district types. Underlying data for this figure are available in sheet "Figure 5" of Supporting Information S2.

rate (STR_{in} : 15% per 10 years, STR_{out} : 7% per 10 years), thereby illustrating the relative differences in material metabolism characteristics across regions. The characteristics of the four groups are as follows:

1. High metabolism: Both STR_{in} and STR_{out} are above the national average, indicating intensive material turnover.
2. Low metabolism: Both STR_{in} and STR_{out} are below the national average, indicating low turnover.
3. Stock accumulation: High STR_{in} but low $STR_{out,}$ suggesting areas with growing stock due to development.
4. Dematerialization: Regions characterized by stock loss.

While the nationwide map suggests that much of the country is characterized by "low metabolism," Figure 6b,c reveals more complex patterns when zooming in on the three major metropolitan areas. Although the four groups are mixed in each region, in the Tokyo metropolitan area, for example, the closer to the center, the fewer "low-metabolism" locations are found. Instead, districts of "high metabolism," "stock accumulation," and "dematerialization" are more prominent, indicating a concentration of regions where material flows are actively occurring some forms.

Hotspots of metabolic activity are highlighted in Figure 6d,g , with enlarged views of several regions where characteristic trends were observed. Figure 7 quantifies the composition ratios of material stock within each of the four categories for these exemplary regions, compared to the national composition.

Central Tokyo (Figure 6d): The 23 special wards are characterized by "high metabolism" and "stock accumulation." Several areas exhibiting "high metabolism" are well known for redevelopment, including the Otemachi, Gaien, and Toranomon districts. Otemachi and Toranomon, in particular, serve as central hubs of Japan's economic activity, where older buildings have been demolished and replaced by new structures (TMG, 2025).

Tsukuba City (Figure 6e): Tsukuba City is a representative Tokyo suburb that has been rapidly growing in recent years (Tsukuba City, 2023). While over 50% of the area exhibits "low metabolism," zones along rail corridors show strong "stock accumulation," corresponding to recent development.

Akita City (Figure 6f): Akita City is the central city of Akita Prefecture, but much of its urban core is classified as undergoing "dematerialization." With the exception of certain areas around Akita Station, where active public investment has been made, many parts of the city center fall into the "dematerialization" category. In contrast, a distinct suburban area is characterized by both "stock accumulation" and "high metabolism." This area, known as Goshono New Town, began residential development around 1980 and has more recently been utilized as an industrial park (Akita City, 2021). It has been suggested that development in this area may have been one of the factors contributing to the hollowing out of the city center (Terasako, 2023).

Kanazawa City and its suburban areas (Figure 6g): Kanazawa City is the central city of Ishikawa Prefecture, and similar to Akita City, its central area exhibits a trend of "dematerialization." While the city center shows a trend of "dematerialization," suburban cities such as Hakusan and Nonoichi exhibit "high metabolism" and "stock accumulation." These suburban districts have experienced population growth as residential areas near Kanazawa, whereas the city center of Kanazawa has been identified as an area affected by urban hollowing out (DBJ, 2025; Kanazawa City, 2023).

In summary, several distinctive districts associated with urban transformation were identified. These patterns are also observable in Figure 7. Central Tokyo is characterized by "high metabolism"; Tsukuba, by "stock accumulation"; Akita and central Kanazawa, by "dematerialization"; and the suburban areas of Kanazawa, by "stock accumulation." Particularly in Akita and Kanazawa, these patterns of material metabolism can be interpreted as metabolic evidence of urban hollowing in traditional city centers, contrasted with urban expansion in suburban areas reflecting urban sprawl.

4 | DISCUSSION

4.1 | Understanding spatial patterns of material stock and flow

This study maps Japan's building material stock over time to conduct a high-resolution spatial analysis of material stocks and flows across the country's buildings, with a particular emphasis on stock turnover. The results reveal clear regional and intra-urban differences in stock–flow conditions, which have been difficult to capture in previous studies that offered either a nationwide time series or high spatial resolution, but not both simultaneously. Investigating interregional differences in turnover enables us to consider the factors that lead to variations in stock–flow patterns and to assess regional resource utilization. This analysis exemplifies how understanding stock–flow dynamics at a broad geographic scale is useful for assessing and comparing resource use under various regional conditions.

From an environmental efficiency perspective, areas with high turnover may be less efficient due to frequent material replacement. Our findings show that regions with dense urban building stocks, particularly those with concentrated urban functions, experience higher levels of both inflows and outflows. This indicates that economically vibrant areas exhibit more intensive material metabolism, reflecting ongoing urban renewal and growth. Such patterns underscore that Japan's urban centers present critical challenges for sustainable resource management. These results underscore the importance of encouraging the long-term use of existing buildings or promoting recycling efforts in such regions.

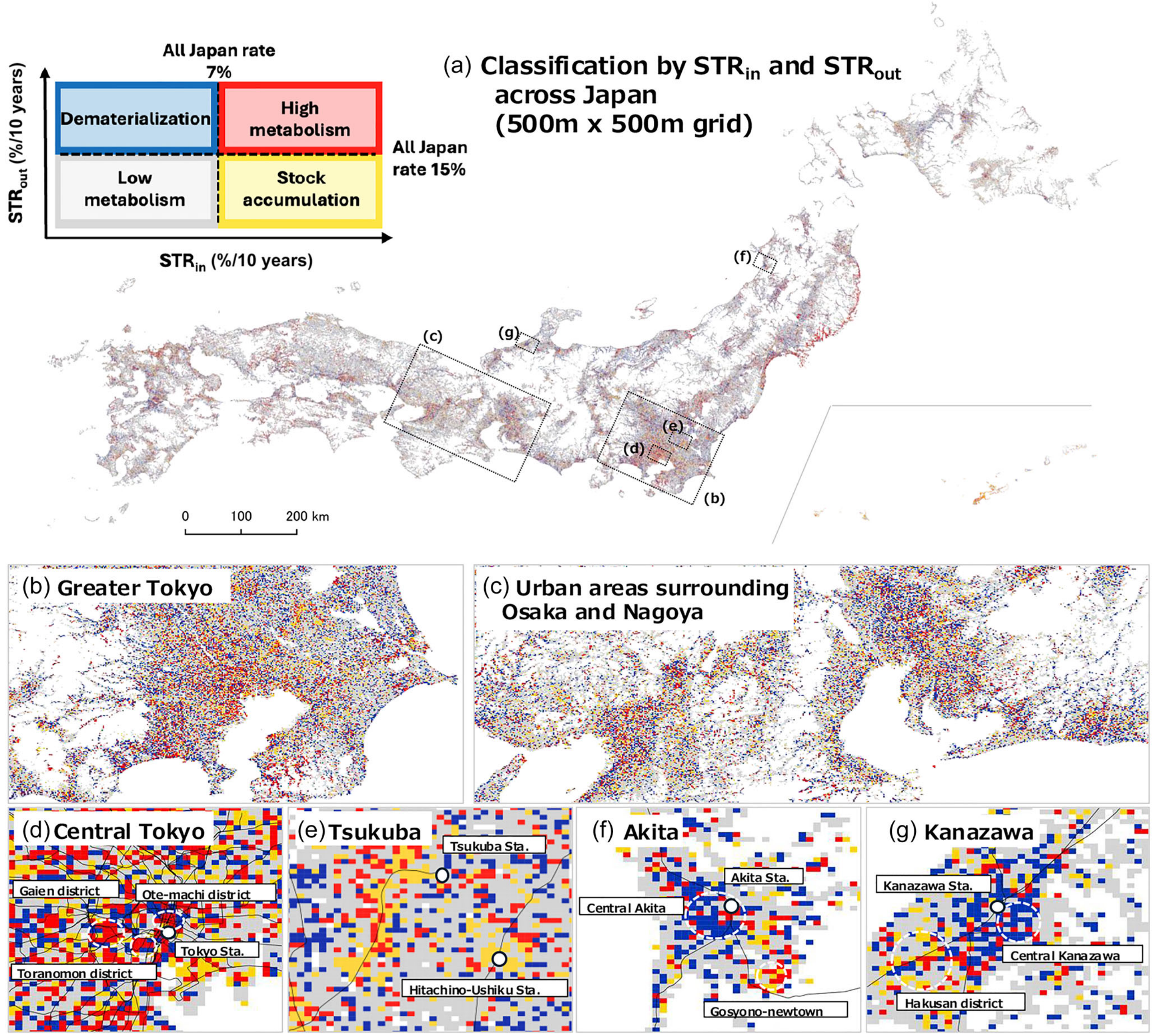

FIGURE 6 Mapping results of material metabolism patterns across Japan (a), with enlarged views of Greater Tokyo (b), urban areas surrounding Osaka and Nagoya (c), central Tokyo (d), Tsukuba City (e), Akita City (f), and Kanazawa City (g).

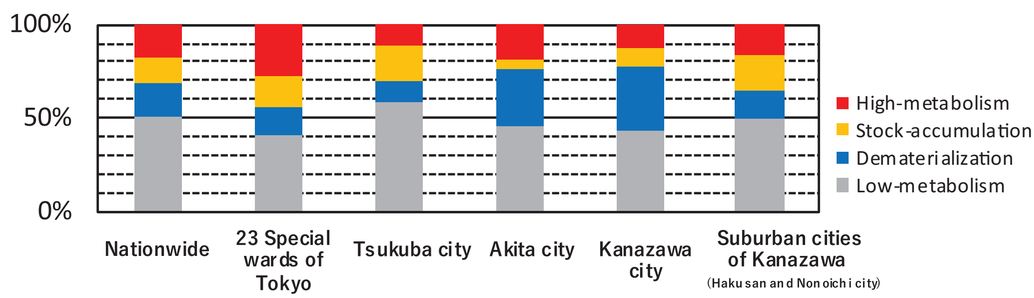

FIGURE 7 Composition ratios of material stock across districts with different metabolism patterns in characteristic cities. Underlying data for this figure are available in sheet "Figure 7" of Supporting Information S2.

Conversely, districts with low turnover rates may seem environmentally sustainable. However, caution is needed when interpreting these areas as inherently sustainable. While low-turnover districts might be efficient in terms of long-term resource use, they can also indicate areas with declining populations and increasing numbers of vacant buildings. Such areas are likely to be less environmentally efficient due to diminished services caused by an increase in underutilized building stock and the essentially short service life (Wuyts et al., 2019) of buildings. Indeed, this study finds low levels of material metabolism in rural areas undergoing population decline. Such areas are likely to experience an increase in underutilized building stock as the population continues to decline. Although stock turnover is relatively slow, careful attention is required from the perspective of long-term stock utilization.

Furthermore, this study reveals that several areas exhibit unique spatial patterns in STR_{in} and STR_{out} in relation to changes in urban form. One of the findings is that, in the context of urban sprawl, different districts may experience distinct material metabolism dynamics—namely, stock loss in city centers and stock accumulation in suburban areas. This indicates a spatially segregated turnover, where depletion and accumulation of stock occur in different locations. It may reflect domino effect (Huuhka & Kolkwitz, 2021) where new construction is triggered in one area while demolitions occur in another. Such spatial separation may indicate that the migration of residential and industrial functions from less attractive city centers to more desirable suburban areas contributes to the underutilization of urban buildings. In response to population decline, many small Japanese cities are currently promoting compact city policies aimed at consolidating urban functions in city centers and improving overall management efficiency (MLITT, 2014b). The results of this study highlight the importance of simultaneously enhancing the attractiveness of city centers and effectively utilizing existing stock in these regions.

Previous research on city-level stocks and flows analysis has demonstrated aspects such as the short lifespans of buildings in redeveloping cities (Guo et al., 2021), differences in metabolic patterns between city centers, suburbs, and newly developing districts (Miatto et al., 2019; Yang et al., 2023), and the factors and patterns that promote building replacement (Huuhka & Kolkwitz, 2021; Kolkwitz et al., 2023). However, it had been difficult to compare material metabolism patterns across various regions as done in this study. As briefly shown in this research, wide-area STR maps provide many samples related to different socioeconomic conditions and diverse material metabolism across regions, enabling the analysis of contributing factors, classification, and relative evaluation. Furthermore, since it covers the entire country, this approach contributes to a more comprehensive understanding of the relationships between stock–flow dynamics and phenomena occurring at the national and regional levels, such as population concentration in cities and changes in urban form.

The regional variation in STR observed in this study is likely closely related to spatial changes in Japan's population distribution. In Japan, the Tokyo metropolitan area has experienced population growth by attracting people from other regions, while many other urban areas have seen only modest increases or even population declines. In addition, many cities are experiencing complex population patterns such as simultaneous population decline in city centers and growth in suburban areas. Findings in this study form a basis for further study into the socioeconomic and demographic drivers of spatial variations in material turnover. Furthermore, the results of this study highlight the importance of promoting sustainable resource use tailored to the specific challenges of each region and district. The Japanese government is promoting recycling of construction materials (MLITT, 2020a) and long-lasting housing (MLITT, 2009) to support sustainable resource management in the construction sector. However, there are currently no plans at district level to monitor or manage building stock or material turnover. For example, considering the high STR in urban areas and the continued population growth expected in these regions, it is necessary to enhance recycling systems in city centers while also providing incentives for renovation rather than rebuilding. Our results highlight the importance—and locations—of such regionally tailored approaches for achieving sustainable management of building stocks.

4.2 | Outlook: Toward the application of high-resolution material metabolism mapping

Looking forward, the database created in this study offers multiple potential applications. A high-resolution map of building stock and turnover reveals where materials accumulate and when they are likely discharged. This supports municipal decision-making by optimizing the placement and capacity of recycling facilities. Moreover, analyzing the spatial supply–demand balance of recycled materials allows designing recycling routes with lower environmental impacts. For example, although central Tokyo's high-metabolism areas and suburban infrastructure demand are far apart, simulating recycling strategies between them can reveal low-impact logistics routes. In addition, since STR is one of the few indicators that directly link stock, flow, and service, it can serve as a more valuable tool for quantitatively identifying and organizing regional resource use challenges when combined with additional indicators such as service provision or material recycling. In particular, if combined with detailed data on how building stock provides services—such as whether buildings are vacant or in active use—this approach may yield high-resolution insights into the interrelationships among stock, flow, and service. This also supports the identification of model districts that exhibit sustainable stock–flow patterns.

Although the analysis provides high-resolution insights, several limitations should be considered. Beyond the well-recognized uncertainties and variabilities inherent to bottom-up stock analyses (Arceo et al., 2023; Lanau et al., 2019; Saxe et al., 2020; Streeck et al., 2025), our approach depends on the availability and accuracy of the spatial data over time. In this study, building replacement was automatically detected based on changes in building footprint data, but slight manual map edits may result in the same building being mistakenly treated as a different one. This could lead to overestimation of material turnover. Additionally, the STR calculated at high spatial resolution can be sensitive to micro-level events within a district—for example, the construction of a single large building in a low-rise area can significantly skew the results. To address this, refining the spatial scale or calculating STR by building type or material category may yield more robust outcomes. Based on such refinements, further classification of the relationships between regional characteristics and material metabolism could reveal more detailed spatiotemporal dynamics of material stock and flow across regions.

Given the potential of STR mapping, a key future research challenge lies in further expanding its temporal and spatial scope. As the current result depends on high-resolution digital data that are only available after 2003, it is limited in its ability to capture long-term dynamics of stock and flow. Therefore, it remains unclear how STR changes over time and with the developmental stages of regions. Moreover, since the present study focuses solely on Japan, the applicability of the findings to other regional contexts remains uncertain. It remains an open question whether our findings are unique to Japan or have broader generalizability. However, our approach can be applied to other countries, once appropriate data become available. The development of datasets covering a wider range of regions will enable international comparisons.

ACKNOWLEDGMENTS

This research was supported by the Environment Research and Technology Development Fund (JPMEERF20231005). This research was also supported by JSPS KAKENHI Grant Numbers JP23H00531, JP24K03140, JP25H01206, MEXT Grant Number JPJ010039, JST Grant Number JPMJPF2204, and European Union ERC-2023-STG project 101116116; Materials-GRoWL: Gauging the Rest-of-the-World's Lifecycles of Construction Materials. This research is also a part of the results of Tokyo University CSIS joint research (No. 1036).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information of this article. The data that support the findings of this study and are not included in the Supporting Information are available from the corresponding author upon reasonable request.

ORCID

Sota Nagata https://orcid.org/0009-0006-2174-2734

REFERENCES

Akita City. (2021). *The 7th comprehensive urban plan of Akita City: Basic policy on urban planning*. Urban Planning Division, Urban Development Department, City of Akita. https://www.city.akita.lg.jp/_res/projects/default_project/_page_/001/029/792/toshikeikaku.pdf (in Japanese)

Arceo, A., MacLean, H. L., & Saxe, S. (2023). Material intensity in single-family dwellings: Variability between locations, functional unit and drivers of material use in Toronto, Perth, and Luzon. *Resources, Conservation and Recycling*, *188*, 106683. https://doi.org/10.1016/j.resconrec.2022.106683

Asakuma, T., Okuoka, K., & Tanikawa, H. (2018). Estimation of accumulation of construction material using identification of buildings in time-series in the Greater Tokyo. *Journal of Environmental Information Science*, *32*, 13–18. https://doi.org/10.11492/ceispapers.ceis32.0_13 (in Japanese)

Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling*, *123*, 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002

Augiseau, V., & Kim, E. (2021). Inflows and outflows from material stocks of buildings and networks and their space-differentiated drivers: The case study of the Paris region. *Sustainability*, *13*(3), 1376. https://doi.org/10.3390/su13031376

B Müller, D. (2006). Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecological Economics*, *59*(1), 142–156. https://doi.org/10.1016/j.ecolecon.2005.09.025

Bai, Y., Yamashita, N., Guo, J., Nagata, S., Shirakawa, H., & Tanikawa, H. (2024). Dynamic analysis of carbon emissions from construction and demolition activities in Japan: Revealed by high-resolution 4D-GIS modeling. *Journal of Environmental Management*, *360*, 121099. https://doi.org/10.1016/j.jenvman.2024.121099

CAA. (2020). *White paper on consumer affairs 2020*. Consumer Affairs Agency. https://www.caa.go.jp/policies/policy/consumer_research/white_paper/assets/consumer_research_cms201_210608_01.pdf (in Japanese)

Cabinet Office. (2020). *Basic approach to urban renewal*. https://www.chisou.go.jp/tiiki/toshisaisei/pdf/kihon-kangaekata.pdf (in Japanese)

Chen, C., Shi, F., Okuoka, K., & Tanikawa, H. (2016). The metabolism analysis of urban building by 4d-GIS – A useful method for new-type urbanization planning in China. *Universal Journal of Materials Science*, *4*(2), 40–46. https://doi.org/10.13189/ujms.2016.040204

CSIS. (2015). *Metropolitan employment area statistics data*. Center for Spatial Information Science. https://www.csis.u-tokyo.ac.jp/UEA/uea_data.htm (in Japanese)

DBJ. (2025). *Urban development proposal for Kanazawa City based on the designation as an urgent urban renewal area*. Development Bank of Japan. https://www.dbj.jp/upload/investigate/docs/4b15d4aa2ddd21519632837b0665096e.pdf (in Japanese)

Frantz, D., Schug, F., Wiedenhofer, D., Baumgart, A., Virág, D., Cooper, S., Gómez-Medina, C., Lehmann, F., Udelhoven, T., Van Der Linden, S., Hostert, P., & Haberl, H. (2023). Unveiling patterns in human dominated landscapes through mapping the mass of US built structures. *Nature Communications*, *14*(1), 8014. https://doi.org/10.1038/s41467-023-43755-5

Fujikawa, Y., Higuchi, T., Ukita, M., Sekine, M., & Imai, T. (2006). Prediction of recycling situation for construction wastes. *Jornal of the Japan Society of Civil Proceedings G*, *62*(1), 53–60. (in Japanese).

Göswein, V., Silvestre, J. D., Habert, G., & Freire, F. (2019). Dynamic assessment of construction materials in urban building stocks: A critical review. *Environmental Science & Technology*, *53*(17), 9992–10006. https://doi.org/10.1021/acs.est.9b01952

Guo, J., Fishman, T., Wang, Y., Miatto, A., Wuyts, W., Zheng, L., Wang, H., & Tanikawa, H. (2021). Urban development and sustainability challenges chronicled by a century of construction material flows and stocks in Tiexi, China. *Journal of Industrial Ecology*, *25*(1), 162–175. https://doi.org/10.1111/jiec.13054

Haberl, H., Wiedenhofer, D., Erb, K.-H., Görg, C., & Krausmann, F. (2017). The material stock–flow–service nexus: A new approach for tackling the decoupling conundrum. *Sustainability*, *9*(7), 1049. https://doi.org/10.3390/su9071049

Haberl, H., Wiedenhofer, D., Schug, F., Frantz, D., Virág, D., Plutzar, C., Gruhler, K., Lederer, J., Schiller, G., Fishman, T., Lanau, M., Gattringer, A., Kemper, T., Liu, G., Tanikawa, H., Van Der Linden, S., & Hostert, P. (2021). High-resolution maps of material stocks in buildings and infrastructures in Austria and Germany. *Environmental Science & Technology*, *55*(5), 3368–3379. https://doi.org/10.1021/acs.est.0c05642

Hashimoto, S., & Moriguchi, Y. (2004). Proposal of six indicators of material cycles for describing society's metabolism: From the viewpoint of material flow analysis. *Resources, Conservation and Recycling*, *40*(3), 185–200. https://doi.org/10.1016/S0921-3449(03)00070-3

Huuhka, S., & Kolkwitz, M. (2021). Stocks and flows of buildings: Analysis of existing, demolished, and constructed buildings in Tampere, Finland, 2000–2018. *Journal of Industrial Ecology*, *25*(4), 948–960. https://doi.org/10.1111/jiec.13107

Kanazawa City. (2023). *Kanazawa City plan for forming a compact urban structure*. https://www4.city.kanazawa.lg.jp/soshikikarasagasu/toshikeikakuka/gyomuannai/1/1/2/syuuyaku/8386.html (in Japanese)

Kolkwitz, M., Luotonen, E., & Huuhka, S. (2023). How changes in urban morphology translate into urban metabolisms of building stocks: A framework for spatiotemporal material flow analysis and a case study. *Environment and Planning B: Urban Analytics and City Science*, *50*(6), 1559–1576. https://doi.org/10.1177/23998083221140892

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). Taking stock of built environment stock studies: Progress and prospects. *Environmental Science & Technology*, *53*(15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652

Mao, T., Liu, Y., Chen, W.-Q., Li, N., Dong, N., & Shi, Y. (2022). Quantifying spatiotemporal dynamics of urban building and material metabolism by combining a random forest model and GIS-based material flow analysis. *Frontiers in Earth Science*, *10*, 944865. https://doi.org/10.3389/feart.2022.944865

MIAC. (2020a). *Summary record of fixed asset values, etc*. Ministry of Internal Affairs and Communications. https://www.soumu.go.jp/main_sosiki/jichi_zeisei/czaisei/czaisei_seido/ichiran08_r03_00.html (in Japanese)

MIAC. (2020b). *List of municipalities comprising mega metropolitan areas and metropolitan areas in 2020 population census*. Ministry of Internal Affairs and Communications. https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00200521&tstat=000001136464&cycle=0&tclass1=000001154126&tclass2val=0 (in Japanese)

MIAC. (2023). *List of core cities*. Ministry of Internal Affairs and Communications. https://www.soumu.go.jp/main_content/000885088.pdf (in Japanese)

Miatto, A., Schandl, H., Forlin, L., Ronzani, F., Borin, P., Giordano, A., & Tanikawa, H. (2019). A spatial analysis of material stock accumulation and demolition waste potential of buildings: A case study of Padua. *Resources, Conservation and Recycling*, *142*, 245–256. https://doi.org/10.1016/j.resconrec.2018.12.011

MLITT. (2008). *White paper on land, infrastructure, transport and tourism in Japan, 2008*. Ministry of Land, Infrastructure, Transport and Tourism. https://www.mlit.go.jp/english/white-paper/2008.pdf

MLITT. (2009). *Basic policy on promoting the spread of long-term quality housing, 2009*. Ministry of Land, Infrastructure, Transport and Tourism. https://www.mlit.go.jp/jutakukentiku/house/content/001753842.pdf

MLITT. (2014a). *Construction recycling promotion plan 2014*. Ministry of Land, Infrastructure, Transport and Tourism. https://www.mlit.go.jp/common/001053889.pdf (in Japanese)

MLITT. (2014b).*Grand design of national spatial development towards 2050, Japan*. Ministry of Land, Infrastructure, Transport and Tourism. https://www.mlit.go.jp/common/001047113.pdf (in Japanese)

MLITT. (2015). *Administrative district data 1920*. Ministry of Land, Infrastructure, Transport and Tourism. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N03-2020.html (in Japanese)

MLITT. (2016). *Hilly and mountainous area data*. Ministry of Land, Infrastructure, Transport and Tourism. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-A25-2016.html (in Japanese)

MLITT. (2020a). *Construction recycling promotion plan 2020*. Ministry of Land, Infrastructure, Transport and Tourism. https://www.mlit.go.jp/common/001053889.pdf (in Japanese)

MLITT. (2020b). *Fact-finding survey on construction by-products*. Ministry of Land, Infrastructure, Transport and Tourism. https://www.mlit.go.jp/sogoseisaku/region/recycle/d02status/d0201/page_020102researchbody.htm (in Japanese)

MLITT. (2020c). *Administrative district data 2020*. Ministry of Land, Infrastructure, Transport and Tourism. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N03-2020.html (in Japanese)

MLITT. (2024). *Densely inhabited district data 2020*. Ministry of Land, Infrastructure, Transport and Tourism. https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-A16-2020.html (in Japanese)

MOE. (2021). *Annual report on the environment, the sound material-cycle society and biodiversity in Japan 2021*. Ministry of the Environment. https://www.env.go.jp/policy/hakusyo/r03/pdf/full.pdf (in Japanese)

MOE. (2003). *Fundamental plan for establishing a sound material-cycle society 2003*. Ministry of the Environment. https://www.env.go.jp/content/900453394.pdf (in Japanese)

NILIM. (2015). *Tsukuba science city's problem on formation process through a present state and subjects*. National Institute for Land and Infrastructure Management Ministry of Land, Infrastructure, Transport and Tourism, Japan. https://www.nilim.go.jp/lab/bcg/siryou/tnn/tnn0815pdf/ks081501.pdf (in Japanese)

Ota, Y., Hiruta, Y., Yamashita, N., Shirakawa, H., & Taniakawa, H. (2023). Material stock and flow estimation by identifying the congruency of urban structures. *Journal of Environmental Information Science*, *37*, 195–201. https://doi.org/10.11492/ceispapers.ceis37.0_195 (in Japanese)

Reconstruction Agency. (2025). Current status and future efforts for reconstruction. https://www.reconstruction.go.jp/topics/main-cat1/sub-cat1-1/20250416genjoutorikumi.pdf (in Japanese)

Saxe, S., Guven, G., Pereira, L., Arrigoni, A., Opher, T., Roy, A., Arceo, A., Von Raesfeld, S. S., Duhamel, M., McCabe, B., Panesar, D. K., MacLean, H. L., & Posen, I. D. (2020). Taxonomy of uncertainty in environmental life cycle assessment of infrastructure projects. *Environmental Research Letters*, *15*(8), 083003. https://doi.org/10.1088/1748-9326/ab85f8

Streeck, J., Baumgart, A., Haberl, H., Krausmann, F., Cai, B., Fishman, T., Lanau, M., Berrill, P., Cao, Z., Deetman, S., Frantz, D., Krey, V., Mastrucci, A., Miatto, A., Pauliuk, S., Rousseau, L. S. A., Saxe, S., Densley Tingley, D., Ünlü, G., & Wiedenhofer, D. (2025). Quantifying material stocks in long-lived products: Challenges and improvements for informing sustainable resource use strategies. *Resources, Conservation and Recycling*, *221*, 108324. https://doi.org/10.1016/j.resconrec.2025.108324

Streeck, J., Wiedenhofer, D., Krausmann, F., & Haberl, H. (2020). Stock-flow relations in the socio-economic metabolism of the United Kingdom 1800–2017. *Resources, Conservation and Recycling*, *161*, 104960. https://doi.org/10.1016/j.resconrec.2020.104960

Tanikawa, H., Fishman, T., Hashimoto, S., Daigo, I., Oguchi, M., Miatto, A., Takagi, S., Yamashita, N., & Schandl, H. (2021). A framework of indicators for associating material stocks and flows to service provisioning: Application for Japan 1990–2015. *Journal of Cleaner Production*, *285*, 125450. https://doi.org/10.1016/j.jclepro.2020.125450

Tanikawa, H., Fishman, T., Okuoka, K., & Sugimoto, K. (2015). The weight of society over time and space: A comprehensive account of the construction material stock of Japan, 1945–2010. *Journal of Industrial Ecology*, *19*(5), 778–791. https://doi.org/10.1111/jiec.12284

Tanikawa, H., & Hashimoto, S. (2009). Urban stock over time: Spatial material stock analysis using 4d-GIS. *Building Research & Information*, *37*(5–6), 483–502. https://doi.org/10.1080/09613210903169394

Tanikawa, H., Managi, S., & Lwin, C. M. (2014). Estimates of lost material stock of buildings and roads due to the great East Japan earthquake and tsunami. *Journal of Industrial Ecology*, *18*(3), 421–431. https://doi.org/10.1111/jiec.12126

Terasako, G. (2023). A turning point for Akita City as a compact city: The policy shift toward new suburban development. *The Jichi-Soken Monthly Review of Local Government*, *49*(539), 49–74. https://doi.org/10.34559/jichisoken.49.539_49 (in Japanese)

Timm, J. F. G., Maciel, V. G., & Passuello, A. (2023). Towards sustainable construction: A systematic review of circular economy strategies and ecodesign in the built environment. *Buildings*, *13*(8), 2059. https://doi.org/10.3390/buildings13082059

TMG. (2024). *Tokyo construction recycling promotion plan*. Tokyo Metropolitan Government. https://www.toshiseibi.metro.tokyo.lg.jp/documents/d/toshiseibi/pdf_seisaku_recy_suishinkeikaku2024 (in Japanese)

TMG. (2025). *Urban development in Tokyo 2025*. Tokyo Metropolitan Government Bureau of Urban Development. https://www.toshiseibi.metro.tokyo.lg.jp/about/pamphlet (in Japanese)

Tsukuba City. (2023). *Statistics of Tsukuba*. https://www.city.tsukuba.lg.jp/material/files/group/15/00_toukeitsukuba2023.pdf (in Japanese)

Wuyts, W., Miatto, A., Sedlitzky, R., & Tanikawa, H. (2019). Extending or ending the life of residential buildings in Japan: A social circular economy approach to the problem of short-lived constructions. *Journal of Cleaner Production*, *231*, 660–670. https://doi.org/10.1016/j.jclepro.2019.05.258

Wuyts, W., Sedlitzky, R., Morita, M., & Tanikawa, H. (2020). Understanding and managing vacant houses in support of a material stock-type society—The case of Kitakyushu, Japan. *Sustainability*, *12*(13), 5363. https://doi.org/10.3390/su12135363

Yamashita, N., Guo, J., Shirakawa, H., & Tanikawa, H. (2021). Empirical research of resource productivity decomposition considering material stock—Case study of Japan's residential buildings. *Journal of the Japan Society of Civil Proceedings G (Environment)*, *77*(6), II_23–II_31. https://doi.org/10.2208/jscejer.77.6_II_23 (in Japanese)

Yang, D., Dang, M., Guo, J., Sun, L., Zhang, R., Han, F., Shi, F., Liu, Q., & Tanikawa, H. (2023). Spatial–temporal dynamics of the built environment toward sustainability: A material stock and flow analysis in Chinese new and old urban areas. *Journal of Industrial Ecology*, *27*(1), 84–95. https://doi.org/10.1111/jiec.13335

ZENRIN CO., LTD. (2020). *Zmap-TOWN II 2003, 2009, 2014, 2016, 2020*. ZENRIN CO., LTD. https://www.zenrin.co.jp/product/category/gis/basemap/zmaptown/index.html (in Japanese)

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Nagata, S., Hasegawa, M., Fishman, T., Shirakawa, H., & Tanikawa, H. (2025). Mapping nationwide material stock turnover: High-resolution spatial analysis of building material stock and flow patterns across Japan 2003–2020. *Journal of Industrial Ecology*, *29*, 2131–2143. https://doi.org/10.1111/jiec.70100