Supplementary Information

For

Declining Demand and Circular Transition Possibilities of Sand, Gravel and Crushed Stone in China

Zijian Ren[1,2,3,#], Meng Jiang[4,#], Paul Behrens[5,6,*], Dingjiang Chen[1,2], Clemens Mostert[7], Wenji Zhou[8], Chunlong Li[1], Fei Li[9], Lin Liu[1], Heming Wang[10], Ming Xu[2,11], Edgar Hertwich[4], Stefan Bringezu[7], Bing Zhu[1,2,12,*]

1. State Key Laboratory of Chemical Engineering and Low-carbon Technology, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China
2. Institute for Circular Economy, Tsinghua University, Beijing, 100084, China
3. Sinopec Engineering Incorporation (SEI), Beijing, 100101, China
4. Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
5. Oxford Martin School, University of Oxford, Oxford OX1 3BD, United Kingdom
6. Institute of Environmental Sciences (CML), Leiden University, Einsteinweg 2, 2333 CC Leiden, the Netherlands
7. Center for Environmental Systems Research (CESR), University of Kassel, 34109 Kassel, Germany
8. School of Applied Economics, Renmin University of China, Beijing 100872, China
9. School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing, 100044, China
10. State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang 110819, China
11. School of Environment, Tsinghua University, Beijing, 100084, China
12. Energy, Climate, and Environment Program, International Institute for Applied Systems Analysis, Laxenburg 2361, Austria

# These authors contributed equally: Zijian Ren, Meng Jiang

* Correspondence and requests should be addressed to: B.Z. (email: bingzhu@tsinghua.edu.cn), or to P.B. (email: p.a.behrens@cml.leidenuniv.nl)

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1.1 Model Framework

1.1.1 Modelling Framework of Aggregate Resource Metabolism

The conceptual framework depicted in Figure S3 illustrates the social metabolism model concerning the lifecycle of aggregate resources. This model categorizes the lifecycle into five distinct phases: extraction, processing, and manufacturing (indicated in yellow); international trade (blue); stock formation and metabolism (orange); waste generation and management (grey); and waste recycling and comprehensive utilization (green).

The sequential flows and processes within each phase are delineated as follows:

Extraction: The primary aggregate resources flow into the social economy through extraction processes such as mining and blasting. This phase encompasses the procurement of various forms of natural minerals, including river sand, lake sand, as well as rock quarries.

Processing: After extraction, raw materials undergo a series of refinement processes. Natural aggregates are cleansed and sorted, while manufactured aggregates are produced through crushing and screening. This stage results in the production of construction-ready aggregates, alongside the processing of secondary materials like tailings, and waste rocks into manufactured aggregates, and CDWs into recycled aggregates.

Manufacturing: In this phase, aggregates are combined with binding agents such as cement and asphalt to fabricate concrete, mortar, and various construction components. Additionally, certain aggregates are directly utilized in their graded form for foundational and substructural applications in some infrastructure projects.

International Trade: For China, despite the predominantly local sourcing and utilization of aggregate resources, a marginal volume of these materials is subjected to international trade.

Stock Formation and Metabolism: Following the manufacturing stage, aggregate resources are integrated into final uses like buildings and roads, constituting a tangible asset base that underpins socio-economic functionalities. Over time, a portion of these assets undergoes metabolic transformation, culminating in their eventual obsolescence and subsequent dismantling, thereby transitioning out of the asset base as waste materials.

Waste Generation and Management: End-of-life aggregate stocks enter the waste management phase, alongside minor quantities of processing and manufacturing waste. Disposal methods for these waste materials include but are not limited to, conventional landfilling and stacking, thereby reintroducing them into the environment.

Waste Recycling and Comprehensive Utilization: A fraction of the aggregate waste is subjected to recovery and sustainable utilization practices, such as backfilling in decommissioned mining sites and foundational pits. Moreover, recycling processes, including crushing and screening, facilitate the production of reclaimed aggregates. Complementary to this, comprehensive utilization strategies are employed to repurpose secondary waste materials like tailings and waste rocks into construction aggregates.

The following sections will detail the model specifics and the material flow balance dynamics inherent to each phase.

(1) Stock Formation and Metabolism

Central to the model, the stock formation and metabolism phase dictates the demand dynamics for aggregate resources within the economic framework and the ensuing generation of waste materials. The analysis is based on an extensive review of literature, annual reports, and databases, categorizing the terminal utilization of aggregates into eight principal categories: building, building sublayers, road, rail, rail transit, pipe, waterworks, parks, etc. Each category encompasses several sub-categories. Employing a dynamic material flow analysis that integrates both stock-driven and flow-driven methodologies, this study delineates the inflows (MF3.1 to MF3.8) and outflows (MF3.9 to MF3.16), alongside the net stock for each sub-category, thereby establishing a critical data foundation for lifecycle accounting across the various phases.

The model of stock formation and metabolism will be introduced in the following section 1.1.2.

(2) Extraction, Processing, and Manufacturing

The analytical delineation of the extraction, processing, and manufacturing stages, as antecedents to the stock accumulation within the model, adheres to the principle of mass conservation. Quantitative assessments within these stages are derived from the inflow metrics and technical parameters associated with each phase, which are, in turn, informed by the data accrued from the stock formation and metabolism phase. The empirical basis for this analysis is anchored on data about the year 2020.

During the manufacturing phase, the utilization of aggregates for cement and asphalt concrete, as well as mortar applications (denoted as MF2.3), is pivotal in the construction of residential buildings, road surface layer, concrete structures within railway and rail transit, parks, and green spaces, waterworks, and pipelines. The formula governing the inflow of aggregates for these applications is encapsulated in Equation 2-1. Conversely, graded gravel (indicated as MF2.4) is integral to the formation of building sublayers and substructural elements across various infrastructural domains, including roads, railways, and rail transit. The corresponding inflow calculation is articulated through Equation 2-2. It is noteworthy that the model does not account for graded gravel within three specific end-use categories—namely, building (excluding building sublayer), waterworks, and parks—owing to their predominant utilization in concrete structures or mortar formulations, thus omitting them from Equation 2-2.

Given the prevalent use of concrete in its fresh or ready-mixed form, which is ill-suited for extensive transportation due to its perishability, the model posits a negligible volume of international trade in concrete commodities. This assertion is further substantiated by the diverse and complex nature of concrete components, rendering cross-border trade minimal when juxtaposed against domestic production volumes. Consequently, the import and export of concrete products within the manufacturing phase are excluded from consideration in this analytical framework.

$$MF2.3 = MF3.1 + \sum \lambda_{3.2,i} \cdot MF3.2_i + \sum \lambda_{3.3,j} \cdot MF3.3_j + MF3.4 + \sum \lambda_{3.5,k} \cdot MF3.5_k + MF3.7 + MF3.8 \tag{2-1}$$

$$MF2.4 = \sum \lambda'_{3.2,i} \cdot MF3.2_i + \sum \lambda'_{3.3,j} \cdot MF3.3_j + \sum \lambda'_{3.5,k} \cdot MF3.5_k + MF3.6 \tag{2-2}$$

$$MF4.1 = (MF2.3 + MF2.4) \cdot \frac{4\%}{1 - 4\%} \tag{2-3}$$

Formulas 2-1 to 2-3 encapsulate the material flow analysis pertinent to the manufacturing phase, wherein the coefficients $\lambda_{3.2,i}$, $\lambda_{3.3,j}$, $\lambda_{3.5,k}$, $\lambda'_{3.2,i}$, $\lambda'_{3.3,j}$, $\lambda'_{3.5,k}$ represent the respective shares of manufacturing outputs in their designated end-uses. $MF2.3$ represents the consumption of aggregates contained in concrete and mortar. $MF2.4$ represents the consumption of aggregates contained in graded gravels. $MF3.1$ to $MF3.8$ represents the consumption of aggregates contained in various final uses, including building, road, rail, pipeline, rail transit, sublayers, waterworks, and parks etc. $MF4.1$ represents the construction waste from processing stage and manufacturing stage in aggregate metabolism.
The coefficients are informed by established guidelines and specifications in China such as the "Highway Engineering Technical Standards," "Highway Subgrade Design Specifications," and "Railway Subgrade Design Specifications." These documents provide insights into the structural composition of highways, railways, and rail transit. According to these standards, the composition of concrete utilized in second-grade (and higher) highways and urban roads comprises 30% aggregates from concrete, with the remaining 70% being graded gravel. Conversely, for lower-grade highways and rural roads, the composition adjusts to 25% aggregates from concrete and 75% graded gravel. In the context of railways and rail transit, the allocation is 70% for aggregates

from concrete and 30% for graded gravel.

The flow of fine aggregates (MF2.1) from the processing to the manufacturing phase denotes the sand component in concrete, whereas coarse aggregates (MF2.2) refer to the stone and graded gravel within the concrete mix. Given the substantial volume of aggregates utilized in residential construction and the variable proportions corresponding to different housing types, the computation for aggregates in residential construction is refined through the application of an intensity coefficient, which varies across housing categories. Furthermore, empirical data and expert consultations indicate that approximately 2% of processing waste is generated during the aggregate processing stage. Similarly, the manufacturing phase also contributes to waste generation, with an estimated 4%[1] of manufacturing waste (MF4.1) from various products being directed towards waste management processes.

The analysis also accounts for a marginal volume of international trade in aggregates (MF6.1, MF6.2), with data sourced from UN Comtrade[2]. The Harmonized System (HS) codes pertinent to this trade are 2505 for fine aggregates and 2517 for coarse aggregates, facilitating the accurate tracking and quantification of these materials in global trade.

$$MF2.1 = \lambda_{2.3} \cdot (MF2.3 - MF3.1) + \sum \lambda_{3.1,i} \cdot MF3.1_i \qquad (2\text{-}4)$$

$$MF2.2 = \lambda'_{2.3} \cdot (MF2.3 - MF3.1) + MF2.4 + \sum \lambda'_{3.1,i} \cdot MF3.1_i \qquad (2\text{-}5)$$

Formulas 2-4 to 2-5 delineate the processing phase. The coefficients $\lambda_{2.3}$ and $\lambda'_{2.3}$ represent the proportions of aggregates utilized in concrete applications, excluding those for building construction. The coefficients $\lambda_{3.1,i}$ and $\lambda'_{3.1,i}$ denote the proportions of aggregates allocated for various types of building construction. Given the diversity in concrete formulations and mix ratios tailored to the specific end-uses of aggregates, the proportions of fine aggregates and coarse aggregates vary accordingly. For precise computation, the model references existing literature[3] to apply distinct coefficients for calculating the fine aggregate and coarse aggregate content in concrete structures across various housing categories. Due to the significant consumption of aggregates in residential construction, a more granular calculation approach is warranted compared to other end-uses. Specifically, the fine aggregate proportions within the aggregate mix for urban residential buildings, non-residential commercial buildings, office buildings, scientific, educational, medical, cultural, and sports buildings, industrial buildings, other non-residential buildings, and rural residences are 52%, 42%, 46%, 43%, 43%, 45%, and 49%, respectively. For concrete structures in other end-uses, a unified coefficient, representing a common mix ratio of 33%, is employed for estimation.

In the extraction phase, the supply of aggregates is computed by accounting for the outputs from the processing phase, including aggregate products, processing waste, and the net balance of aggregate trade. The study categorizes aggregates into natural

(MF1.1) and manufactured (MF1.3) types. Utilizing data on the annual supply-side proportion of natural versus manufactured aggregates[4], the study estimates the supply volumes for both categories. Additionally, incorporating data on tailings and waste rock (MF5.1) from the "China Resource Comprehensive Utilization Annual Report [5]" alongside calculations from the recycling module for recycled aggregates (MF5.2), enables the determination of the mining volumes for primary aggregates.

$$MF1.1 = \lambda_{1.1} \cdot (MF2.1 + MF2.2 + MF4.1 + MF6.2 - MF6.1 - MF5.2) \quad (2\text{-}7)$$

$$MF1.3 = \lambda_{1.3} \cdot (MF2.1 + MF2.2 + MF4.1 + MF6.2 - MF6.1 - MF5.2) \quad (2\text{-}8)$$

$$MF1.2 = MF1.3 - MF5.1 \quad (2\text{-}9)$$

Formulas 2-7 to 2-9 are the material flow accounting process in the extraction phase, where $\lambda_{1.1}$ is the proportion of natural aggregates on the supply side, and $\lambda_{1.3}$ is the proportion of manufactured aggregates and recycled aggregates. The sum of the two parameters is 1. According to expert consultation from the China Aggregates Association, natural aggregates accounted for 17.3% of the aggregate supply in 2020.

$MF1.1$ represents the extraction of natural aggregates. $MF1.2$ represents the extraction of raw stone which will be processed into crushed stone ($MF1.3$). $MF5.1$ represents tailings and waste rock which are comprehensively used as crushed stone. $MF6.1$ and $MF6.2$ respectively represent the aggregate import and export.

(3) International Trade

The material flow of aggregates includes a minor degree of international trade(MF6.1, MF6.2), with data sourced from the United Nations Commodity Trade Statistics Database (UN Comtrade[2]). The Harmonized System (HS) codes applicable to this trade are 2505 for fine aggregates and 2517 for coarse aggregates. Given the perishable nature of concrete in its fresh or ready-mixed states, which renders it unsuitable for long-distance transport, the import and export activities related to concrete are virtually nonexistent. Moreover, the international trade of concrete products is negligible in comparison to domestic production volumes. Consequently, the trade of aggregates embodied within concrete products during the processing and manufacturing phase is excluded from this analysis.

(4) Waste Generation and Management

Waste generation (MF4.3) encompasses both processing and manufacturing waste (MF4.1) and various categories of demolition waste (MF4.2) that emerge from the metabolic breakdown of structures after their lifecycle. The demolition waste (MF4.2) of aggregates is the sum of all the outflows (MF3.9 to MF3.16) from various categories of final uses.

$$MF4.3 = MF4.1 + MF4.2 \quad (2\text{-}10)$$

$$MF4.2 = MF3.9 + MF3.10 + MF3.11 + MF3.12 + MF3.13 + MF3.14 + MF3.15 + MF3.16 \quad (2\text{-}11)$$

Post-disposal, aggregate waste can either be released into the environment (MF4.4), recycled (MF5.2), or subjected to comprehensive utilization (MF5.3).

(5) Waste Recycling and Comprehensive Utilization

The calculation of fillings (MF5.3) and recycled aggregates (MF5.2) draws upon data from relevant reports and literature[5], applying specific coefficients to each waste category. Land-filled aggregate waste (MF4.4) is deduced by subtracting the volumes of fillings and recycled aggregates from the total waste generated, following the principle of mass conservation.

$$MF5.2 = \lambda_{5.2} \cdot (MF3.9 + MF3.12 + MF3.14 + MF3.15 + MF3.16) + \lambda'_{5.2} \cdot (MF3.10 + MF3.11 + MF3.13) \quad (2\text{-}12)$$

$$MF5.3 = \lambda_{5.3} \cdot (MF3.9 + MF3.12 + MF3.14 + MF3.15 + MF3.16) + \lambda'_{5.3} \cdot (MF3.10 + MF3.11 + MF3.13) + \lambda''_{5.3} \cdot MF4.1 \quad (2\text{-}13)$$

$$MF4.4 = MF4.3 - MF5.2 - MF5.3 \quad (2\text{-}14)$$

Formulas 2-12 to 2-14 detail the material flow accounting for waste recycling and comprehensive utilization. The coefficients $\lambda_{5.2}, \lambda'_{5.2}$ are the recycling rate of waste, and $\lambda_{5.3}, \lambda'_{5.3}, \lambda''_{5.3}$ are the comprehensive utilization rate of waste. According to China Resource Comprehensive Utilization Annual Report[6,7] and expert consultations, the utilization rates of aggregate waste from concrete parts of residential construction, waterworks, and processing waste are as follows: 8% is recycled, with 60% used for recycled aggregates and 40% for comprehensive utilization such as backfilling. For aggregate waste from concrete parts of roads, railways, and rail transit, the utilization rate is 40%, with 20% allocated for recycling as road materials and 80% for comprehensive filling utilization[7].

The model's framework ensures comprehensive coverage of all aggregate use in the economic system, with recycling rates indicating the proportion of waste repurposed for the end-use categories in this study, and comprehensive utilization rates indicating the share of waste employed for backfilling, ecological reclaiming, and other applications not explicitly covered within the model's scope, such as land remediation.

1.1.2. Modelling Framework of Provincial-level Dynamic Material Flow Analysis

(1) Principles and Overview

This study employs a dynamic material flow model to investigate the metabolic processes associated with the final use of aggregate resources across eight main categories and thirty sub-categories within the socio-economic context, facilitating the computation of annual inflows, outflows, and stocks. Previous research[8-10] predominantly focused on the utilization of aggregates only in housing, road, and railway applications, often neglecting a comprehensive assessment of the demand spectrum. This oversight led to potential inaccuracies due to incomplete categorization and the risk of data omission or duplication. To address these challenges, the current study incorporates a broad array of end uses for domestic aggregate resources, informed by expert opinions, literature reviews, and database analyses, thereby ensuring a detailed categorization of end uses. This approach enhances the model's ability to accurately represent the flow and stock of aggregate resources, shedding light on the intricate demand-side structure.

As illustrated in Figure S4, the model integrates a flow-driven dynamic material flow component and a stock-driven counterpart, predicated on the available data and the logical coherence of the model's construction. The discussion herein focuses on the flow-driven aspect of the model, which is predicated on the conservation of mass principle, asserting that the stock increment equates to the net inflow. This principle is encapsulated in Formula 2-14, where the current year's stock is the sum of the previous year's stock and this year’s net inflow. The outflow calculation, represented in Formula 2-15, employs a dynamic metabolism approach, aggregating the metabolized inflows from all preceding years to determine the current year's outflow.

$$Stock[n] = Stock[n-1] + (Inflow[n] - Outflow[n]) \qquad (2\text{-}14)$$

$$Outflow[n] = \sum_{t=1}^{n-1} Inflow[n-t] \cdot f(t,\mu,\sigma) \qquad (2\text{-}15)$$

$$f(t,\mu,\sigma) = \left(1/\left(t \cdot \sigma \cdot \sqrt{2\pi}\right)\right) \cdot \exp(-(ln(t)-\mu)^2/2\sigma^2) \qquad (2\text{-}16)$$

$$E(X) = exp(\frac{\mu + \sigma^2}{2}) \qquad (2\text{-}17)$$

$$D(X) = (exp(\sigma^2) - 1)exp(2\mu + \sigma^2) \qquad (2\text{-}18)$$

$Stock[n]$, $Inflow[n]$, and $Outflow[n]$ refer to the aggregate stock, inflow, and outflow in year n; t, μ, and σ are parameters of the lognormal distribution $f(t,\mu,\sigma)$. They determine the location parameter $E(X)$ and the scale parameter $D(X)$ of the lognormal distribution.

The model necessitates initial value assignments for either the starting stock in the flow-driven model or the initial inflow in the stock-driven model, utilizing a forward expansion methodology for time series data to establish these initial values. Given the post-1978 economic and social development phase in China, this study focuses on data from this period onwards, setting 1949 as the base year for calculations. The inflow for 1949 is treated as the initial stock, with subsequent data from 1949 to 1977 being excluded from the final analysis. This approach is deemed appropriate due to the relatively short lifespan of China’s buildings at that time, which mitigates the impact of pre-1949 data absence on the accuracy of post-1978 stock and flow estimations[1].

The metabolic characteristics of China's buildings and infrastructure stocks inform the selection of the lognormal distribution as the model's probability density function [11,12], as detailed in Formula 2-16. The distribution parameters and their relationships are further elaborated in Formulas 2-17 and 2-18. In previous studies[1,12], researchers used the delta distribution, Weibull distribution, normal distribution, log-normal distribution, beta distribution, and gamma distribution, etc. for different types of materials. The distribution was chosen according to available lifetime data for the considered products or end-use sectors. Miatto et al. discussed that the log-normal distribution, and in general right-skewed distribution works best for short-lived buildings, which are typical of China[11]. Also, we follow the previous study[13] on China’s buildings and infrastructure to use the log-normal distribution as the lifetime distribution in the present study. The standard deviation of all kinds of final uses is 30% of the expected lifetime.

This dynamic material flow model extends the static framework presented in Figure S3 by incorporating the dynamic-stock dimension, where the $Inflow[n]$ and $Outflow[n]$, denoted in Formulas 2-14 and 2-15, correspond to MF3.1 to MF3.8 and MF3.9 to MF3.16 in Figure S3, respectively. This integration enriches the model's capability to capture the nuanced dynamics of aggregate resource utilization.

(2) Provincial-Level Model

Aggregate exemplify materials with pronounced local characteristics, primarily due to their bulk nature and relatively low value per unit, leading to a predominantly local extraction and consumption pattern. This localized dynamic underscores the necessity of examining the metabolism of aggregate resources at subnational scales. Such an analysis is pivotal for informing policy decisions pertinent to local aggregate industries and facilitating the formulation of national policies that promote balanced regional development.

In alignment with the foundational principles of the model delineated previously, this investigation assesses the historical stock and flow of aggregate resources at the provincial level. This is achieved by developing a comprehensive database encompassing extensive aggregate data at this granularity. As depicted in Figure S4, the model elucidates the structure of input data and the results of the social metabolism model for aggregate resources at the provincial level. The outcomes encompass the inflow, outflow, and stock corresponding to diverse end uses across China's 31 provinces spanning the period from 1978 to 2020.

The compilation of data at the provincial level presents significant challenges, stemming from the non-uniformity of statistical systems and the variance in statistical indicators across provinces. Additional challenges are compounded by regional disparities in construction practices, material utilization, and other factors influenced by local conditions and climatic variations, necessitating tailored adjustments to material intensity parameters and other model variables through extensive literature review and expert consultations.

In terms of model application, the flow-driven dynamic material flow model is employed to quantify the stock and flow associated with urban residential buildings, non-residential buildings, waterworks, and building sublayers. Conversely, the stock-driven dynamic material flow model is utilized for assessing the stock and flow related to roads, rail transit, railways, pipelines, rural housing, parks, green spaces, etc.

Subsequent sections will provide a comprehensive exposition of the underlying data types employed within the model, elucidating their relevance and application within the provincial-level analysis framework.

1.2 Data and sources

The section on the historical evolution of underlying data in this study, exemplified by data from 2020, delineates the origins, estimations, and organizational structure of the data utilized. In Table S11, taking Beijing as an example, we list the underlying data, coefficients, as well as the specific values of life expectancy and their data sources for various final uses. The data sources for each province are similar, with the underlying data primarily coming from yearbooks or statistical bureau websites, coefficients derived from literature, standards, reports, and expert consultations, and life expectancy values sourced from literature, standards, and expert consultations. All data used in this study are open-access. The sources are available in either English or Chinese. For Chinese-language sources, we have noted ‘in Chinese’ in the reference list.

This overview encompasses:

1.2.1. Building

(1) Data

The continuity of provincial-level statistical data concerning the completed area of buildings presents challenges. As indicated in Table S2, the underlying data for buildings is derived from an analysis of the completed area of housing in society and the completed area of buildings in the construction industry. The detailed data sources for buildings are also listed in Table S2.

Notably, the establishment dates of some provincial-level administrative regions postdate the study's temporal scope (1949-2020). For instance, Chongqing became a direct-governed municipality only in 1997. Nonetheless, pre-establishment statistical data for such regions, like Chongqing's data before 1996, is available in the statistical bureau and considered relevant for this analysis. This study posits that geographical areas, irrespective of their administrative status, maintain a degree of economic and social autonomy. Consequently, to ensure model coherence and historical continuity, data from periods preceding the formal establishment of certain administrative regions are incorporated into the analysis.

To address gaps in early-year regional data, interpolation estimates are applied. Additionally, discrepancies in early-year data between the completed area of housing in society and the completed area of buildings in the construction industry, as recorded by the National Bureau of Statistics, are reconciled by adjusting residential housing figures to align with total housing area data when the former exceeds the latter.

A specific note is needed regarding the service life of buildings. During China's rapid development, policy-driven large-scale demolition and reconstruction have led to many buildings being dismantled well before reaching their expected service life[14]. As a result, the actual service life of buildings in China over recent decades has been relatively shorter than that in developed countries such as those in Europe and North America.

(2) Intensity Coefficient

The material intensity coefficients for various types of housing construction across provinces are derived from a comprehensive review of reports and literature[15]. These coefficients are aligned with national-level material intensity coefficients[16], with provincial allocations made according to the corresponding years to reflect regional construction practices.

This approach to data construction and intensity coefficient formulation enables a nuanced analysis of regional building construction trends and materials usage, facilitating a deeper understanding of the evolutionary patterns in building construction across China's provinces.

1.2.2. Building sublayers

Building sublayers are the structural base that supports a building or structure by distributing its weight to the ground, ensuring stability and preventing settlement or movement. It is designed based on the soil type and load requirements of the structure.

(1) Data

The assessment of building sublayers' stock and flow at the provincial level primarily relies on cement consumption data[17]. The cement consumption in each province is derived from cement production, as reported by the National Bureau of Statistics[18], and net import. Given the absence of detailed provincial import and export statistics for cement and the fact that the net import volume of cement nationally is typically less than 1% of total production, a simplified estimation approach is adopted. This method apportions the national cement import and export volumes to each province in proportion to their respective production figures, thereby estimating the cement import and export volumes at the provincial level.

(2) Intensity Coefficient

Considering the relatively minor volume of aggregates utilized in building sublayers, its impact on the overall calculation of aggregate stock and flow is deemed negligible. Consequently, the material intensity coefficients for building sublayers in each province are established by referencing national-level coefficients[16].

1.2.3 Roads and Other Infrastructure

(1) Data

The foundational data for provincial highway mileage is primarily sourced from the EPS Macroeconomic and Transportation Database[19]. Data about urban and rural road mileage at the provincial level is mainly derived from the EPS China Urban and Rural Construction Database[19], alongside China Urban Construction Statistical Yearbook[20] and China Urban and Rural Construction Statistical Yearbook[21]. It's noted that statistical data for urban roads pre-2001, county and township roads pre-2005, and rural roads pre-2012 at the provincial level is lacking. In these instances, national statistics and the distribution patterns from adjacent years are utilized for apportionment.

Railway operating mileage data, both general-speed and high-speed, at the provincial level, is obtained from the National Bureau of Statistics[18]. The apportionment of extended mileage for ordinary national railway mainlines is based on each province's share of total railway operating mileage. High-speed rail mileage data at the provincial level is sourced from the EPS Transportation Database[19].

Provincial rail transit mileage data is compiled from various sources: pre-2009 data from the Wind database, 2010-2019 data from the EPS China Transportation Database[19], and 2020 data extrapolated from 2017-2019 figures.

Pipeline mileage data at the provincial level is collected from the EPS China Urban and Rural Construction Database[19] and the EPS China Urban Construction Database[19].

Data on concrete usage in provincial waterworks is drawn from the EPS Waterworks Database[19] and China Water Statistical Yearbook[22], with pre-2000 provincial data apportioned based on the 2000 provincial statistics in proportion to national figures for the corresponding years.

Data on provincial parks and green spaces is acquired from the National Bureau of Statistics[18,23].

(2) Intensity Coefficient

Given that infrastructure projects like roads and railways typically adhere to national standards, the intensity coefficients for such constructions within each province are set about the national benchmarks[24-28].

Specifically, for roads, we referred to technical standards related to road construction.[24-26], The roads are divided into the surface layer and sublayer, with different materials, strength coefficients, and service lives for each layer. We have provided the detailed values in the *Supplementary_Dataset_Underlying data & Parameters.xlsx*. In reality, different types of roads have varying structures; for instance, some roads have three layers—surface layer, base layer, and subbase layer—and construction can vary depending on geological and topographical conditions. However, given the macro-level scope of our research, it is not feasible to account for every specific road. Therefore, we adopted the approach of simplifying the roads into two layers for calculation purposes.

Similar to roads, railways are also divided into different types[27,28], including ballasted railways, ballastless railways, single-track railways, and double-track railways, among others. Railway construction also consists of different layers. However, considering that the demand for gravel in railways constitutes a relatively small portion of the total gravel demand—less than 5%—we simplified the railway structure by considering it as a single layer for the purpose of our study.

For rail transit and pipelines, we set the strength coefficients based on the relevant literature[29-32]. For waterworks, the construction primarily relies on concrete. We referred to national standards[33] and concrete mix proportions[34,35] to determine the strength coefficients.

1.3 Missing and Abnormal Data Handling

In instances where statistical data for certain provinces or years is missing, interpolation methods are generally employed to fill these gaps[36]. When output data for specific provinces shows a decreasing trend in the stock of an item over time, which may be attributed to systematic factors like changes in statistical definitions, the stock-driven dynamic material flow model might yield negative inflow figures. In such cases, model outputs are adjusted, employing interpolation to rectify negative values. This adjustment approach is not expected to significantly affect the model's iterative calculations in subsequent years, in line with the characteristics of the dynamic material flow model's life distribution function.

1.4 Regional Grouping

In our research, the categorization of China's economic regions is informed by pivotal policy documents including "Several Opinions of the Central Committee of the Communist Party of China and the State Council on Promoting the Rise of the Central Region", "Opinions on the Implementation of Several Policies and Measures by the State Council on the Development of the Western Region", and insights from the report presented at the 16th National Congress of the Communist Party of China. This delineation segments China into four principal regions: Eastern, Central, Western, and Northeastern. For an elaborate delineation and visual representation of these regional divisions, Figure S2 in our study provides comprehensive details.

The composition of each regional category is as follows:

- Northeastern Region: This area encompasses Liaoning Province, Jilin Province, and Heilongjiang Province.
- Eastern Region: This sector includes a broad array of provinces and special administrative regions, namely Beijing, Tianjin, Hebei Province, Shanghai, Jiangsu Province, Zhejiang Province, Fujian Province, Shandong Province, Guangdong Province, Hainan Province, and the special administrative regions of Hong Kong and Macao, along with Taiwan Province.
- Central Region: Constituted by Shanxi Province, Anhui Province, Jiangxi Province, Henan Province, Hubei Province, and Hunan Province.
- Western Region: This extensive area comprises Inner Mongolia Autonomous Region, Guangxi Zhuang Autonomous Region, Chongqing Municipality, Sichuan Province, Guizhou Province, Yunnan Province, Tibet Autonomous Region, Shaanxi Province, Gansu Province, Qinghai Province, Ningxia Hui Autonomous Region, and Xinjiang Uygur Autonomous Region.

1.5 Uncertainty analysis of CHAMPS

The CHAMPS model incorporates a large-scale set of underlying data, intensity coefficients, distribution functions, and other parameters. There are complex interrelationships between the internal modules of the model, as well as various algorithms. The parameters involved in this model come from yearbooks, literature, databases, etc., and the precision of the data carries certain uncertainties. Additionally, the robustness of the model itself requires further examination.

We use a Monte Carlo simulation as an uncertainty analysis of the CHAMPS model. We anchored all model parameters and performed 10,000 random samples within specific ranges in normal distribution, with a confidence level of 95.5%[16]. These 10,000 sets of parameters were then applied to the CHAMPS model for repeated calculations, producing 10,000 results.

The specific range is determined by the types of final uses according to the data availability and precision. As shown in Table S15, we referred to relevant literature[1] and considered factors such as the availability of China's underlying data on aggregate resources, the reliability of data sources, and other relevant aspects. Based on this, we differentiated the input values of underlying data and the deviation of uncertainty distribution for the lifespan values across various final uses.

We assume normal distributions in the Monte Carlo simulations as both positive and negative deviations are equally probable, with the majority of values concentrated near the mean. Such an assumption is widely accepted for estimating data uncertainties, especially in the absence of more specific information, and is common practice[1].

The results of the Monte Carlo simulations are shown in Figures S28–S33. The analysis shows that most variations fall within ±30.9% for inflows, ±16.9% for stocks, and ±49.9% for outflows across provinces (Supplementary Figures S28–S30). Monte Carlo simulation serves not only to quantify uncertainties in model results but also functions as a robustness sensitivity analysis for the model. The sensitivity analysis is reflected by how much deviation in input parameters propagates to the output results. As comprehensively reviewed by Nađa Džubur et al. regarding sensitivity analysis approaches for dynamic material flow models[37], this study falls under their classification of Local Sensitivity Analysis with Uncertain Parameters (LSAu). In this context, robustness refers to the relative insensitivity of model outputs to plausible variations in input assumptions. As the output variability does not exceed the assigned input uncertainty ranges (15–60%), the model is considered proportionally stable under uncertainty propagation, consistent with practices in MFA-related Monte Carlo modeling. Therefore, the differences between the maximum and minimum data points for each year are considered acceptable. In addition, the uncertainty in aggregate-related data is inherently quite large. According to a UNEP report[38], the global uncertainty in aggregate inflows is about 25% (40–50 Gt). In the study by Krausmann et al.[1], a 60% uncertainty level was applied to aggregate inflows in Monte Carlo simulations. These references further support the plausibility of our uncertainty settings and results. This also explains why we used relatively large uncertainty ranges for the input parameters. Notably, due to the high resolution of our model, we estimated uncertainties separately for different end uses of aggregates (Figures S31–S33). For major applications such as buildings and roads, only slight variations were observed, and the results showed good consistency.

As shown in Table S16, the Monte Carlo simulation results present the maximum deviation values of inflows, outflows, and stocks of gravel resources in each province during the retrospective analysis. The maximum deviation of aggregate demand in most provinces is within 25%, the maximum deviation of aggregate stocks is generally within 12%, and the maximum deviation of aggregate stock outflows is within 49%. It is important to note that these are maximum deviation values. Under the parameters of the Monte Carlo simulation in this study, the average deviation of all results is less than 50% of the maximum deviation. Therefore, the robustness of the model in this study is satisfactory.

2 Scenario analysis

This study has developed a future scenario model for the social metabolism of China's (provincial) aggregate resources. This was based on constructing a future scenario framework and developing a social metabolism model specific to China's aggregate resources.

In this model, we calculated the projected stock and flow data of sand and gravel resources across various provinces and categories, under different scenarios. Additionally, we analyzed the transformations in industrial structure on the supply side.

2.1. Scenario Model Framework

Illustrated in Figure S5, the present study synthesizes prevailing trends within China's aggregate industry, Shared Socioeconomic Pathways (SSP), circular economy principles (3R), and a social metabolism model for China's aggregate resources as depicted in Figures S3 and S4, to establish a comprehensive scenario analysis framework for the prospective management of aggregate resources at a provincial level within China. This framework acknowledges the intrinsic local characteristics of aggregate resources, thereby enhancing the robustness of policy support for regional industry development while accommodating the developmental disparities across Chinese provinces through high-resolution provincial data, thereby bolstering the reliability of bottom-up scenario analyses. Leveraging an extensive database on the historical evolution of provincial aggregate resource metabolism, the study embarks on a scenario analysis focused on the anticipated societal metabolism of these resources at a provincial scale.

We would like to clarify that our analysis does not include pessimistic scenarios in which projected outcomes fall below the baseline. This decision is grounded in both empirical evidence and methodological reasoning. China currently consumes approximately 20 billion tons of aggregates annually—an extraordinarily high volume. Given the conditions in recent years, demographic trajectory, and the observed shift from rapid growth to sharp decline in total consumption since 2015, there is limited justification for constructing scenarios that assume even higher future demand. It is unlikely that China will experience the same scale of construction needs as in previous decades.

Excluding such pessimistic pathways is also consistent with established modeling practices, which prioritize empirically grounded trajectories over speculative downturns. For example, in the global scenario analysis by Zhong et al. [39], the baseline scenario itself represents the conservative projection. Our study focuses on assessing the potential impacts of circular economy strategies on China’s aggregate sector. Within this context, the baseline scenario provides a sufficient and appropriate reference point, without the need to incorporate explicitly pessimistic pathways.

The foundational data for this analysis is predicated on the projected evolution of stock for varied end uses, the structural composition of final demand, trajectories of economic and social indicators, and lifespan distributions of end uses. Initially predicated on the extant development paradigm of China's aggregate industry and intermediate development path scenario (SSP2) macroeconomic insights, baseline scenario demand-side data is constituted. Subsequently, scenarios predicated on circular economy tenets (3R) are developed atop the baseline scenario, culminating in three distinct scenarios encapsulating Intensive Use, Lightweight Design, and Lifetime Extension, each with bespoke foundational demand-side data. The integration of these scenario-specific data into an augmented stock-driven dynamic material flow model facilitates the computation of demand-side stocks and flows of various end uses for each province in future projections.

By channelling demand-side stock and flow data into the supply-side analysis, while intertwining an improved recycling scenario with circular economy tenets, and factoring in the entire lifecycle metabolic process of aggregate resources, the study delineates the future supply framework for natural sand and gravel, crushed stone, and recycled aggregates.

Considering the temporal aspect, this investigation aims to delineate the medium to long-term trajectory of China's aggregate industry, aligning with the national ambition of evolving into a fully developed socialist country by 2050. Hence, the temporal scope for scenario analysis spans from 2021 to 2050.

2.2. Demand-Side Model Formulation under Baseline Scenario

For model construction expediency within the future stock evolution scenario framework, end uses delineated in Figure S4 are aggregated into nine principal categories based on their indicative and socio-economic characteristics, with detailed computations conducted for seventeen subcategories. Concurrently, eight scenario variable groups corresponding to diverse end-use inventory calculation methodologies are formulated. The interrelations between these diverse end-use data constructions, scenario variable configurations, and their corresponding dynamics are elucidated in Figure S8.

External economic and social indicator variables adopt the SSP2[40] intermediate pathway, fostering a robust scenario framework conducive to economic and social adaptation and mitigation strategies toward climate change challenges. This alignment not only ensures consistency with the prevailing global discourse on climate change but also aptly characterizes the evolution of China's principal economic and social indicators under the "double carbon" objective within the shared socioeconomic pathways (SSP1-5) [40] framework, with material resource scenario analyses predominantly leveraging the SSP2 pathway characterized by moderate mitigation and adaptation capabilities[39]. The future developmental trajectories of GDP, population[41], and built-up areas[42] for each province under the SSP2 pathway are derived from extant literature.

Utilizing model computations for scenario variables corresponding to various end uses, as depicted in Figure S8, facilitates the analysis of stock evolutions within future scenarios. This involves integrating life distribution functions of end uses into the dynamic material flow model to derive inflow and outflow data.

Outlined in Figure S6, the overarching model framework for future scenario analyses of the social metabolism of aggregate resources on the demand side encompasses:

I. The historical per capita stock or density for each specific end use is computed, with future projections for saturated per capita stock or density being established based on pertinent plans, documentation, and other relevant sources.
II. The evolution of stock is observed to follow an S-shaped trajectory[39,43], correlating with stages of economic development. This pattern is modelled using logistic curve regression, which is then integrated with projections of future per capita GDP to estimate future per capita stock levels.
III. Future stock levels are determined by calculating the anticipated stock density and integrating this with the foundational stock density, thereby deriving the total future stock.
IV. Employing the dynamic material flow analysis (d-MFA), the study utilizes diverse models tailored to various end uses. This involves the integration of dynamic material flow models driven by historical inflows, historical stocks, and anticipated future stocks. Through this integration, the study ascertains the stock and flow data for a wide array of end uses, projecting into the future.

2.3. Supply-Side Model Formulation under the Baseline Scenario

The framework for analyzing the supply-side scenario of aggregate resources is delineated in Figure S7. The supply structure of China's aggregate resources is bifurcated into primary and recycled categories based on their origins. The primary category encompasses both natural sand and gravel and crushed stone. Given the negligible impact of aggregate imports and exports on overall consumption, coupled with China's self-sufficiency in aggregate mineral resources, international trade of these resources is omitted from the scenario analysis. The supply-side calculation adheres to the following principles:

Recycled Aggregates: The generation of recycled aggregates is quantified based on the outflow of aggregate waste from various stocks, as identified in the demand-side scenario analysis. This calculation employs predefined recycling rates to determine the volume of recycled aggregate produced.

Natural Sand and Gravel: Future mining volumes for natural sand and gravel are projected based on historical extraction data for river sand, lake sand, and other forms of natural sand and gravel. This projection also incorporates river sediment transport data and other relevant metrics to establish future mining volumes for natural sand and gravel.

Crushed Stone: The supply of crushed stone in future scenarios is derived by analyzing the inflow of various stocks from the demand-side scenario analysis and applying the principle of material conservation. This involves deducting the calculated supplies of recycled aggregates and natural sand and gravel from the total projected demand to ascertain the future supply of crushed stone.

The detailed computational process under the baseline scenario for the supply side encompasses these three key components, ensuring a comprehensive evaluation of future sand and gravel resource availability. This methodological approach facilitates a nuanced understanding of the potential shifts in resource supply dynamics, aligning with the overarching objectives of sustainable resource management and environmental conservation.

2.3.1 Recycled Aggregates

Based on outcomes from the demand-side scenario analysis, projections for the future stock and flow associated with various end uses are established. Within this framework, stock outflows represent the volumes of aggregates contained within demolition waste from diverse end uses. Moreover, a quantifiable volume of aggregate waste arises during processing and construction activities. Based on our previous work[16], this study posits a future scenario where aggregate waste from processing and construction activities will linearly decrease from 4% to 2% of the stock inflow between 2021 and 2050. This projection facilitates the estimation of future aggregate waste volumes across different provinces.

Recycling methodologies and rates vary significantly across different types of end-use-generated aggregate waste. Notably, as depicted in Figure S7, achieving a 100% recycling rate for various aggregate waste types is challenging, with a portion typically designated for comprehensive use as fillings or landfill post-disposal. For the fraction amenable to recycling, this study incorporates considerations for technical and transportation factors inherent to the recycling processes of diverse waste types. Specifically, a segment of the construction-generated aggregate waste is earmarked for recycling within the building construction, with a portion being downcycled for use in infrastructure applications such as road cushions and concrete blocks.

Under the baseline scenario, the recycling and downcycling rates for aggregate waste from various end uses are benchmarked against the prevailing conditions[7,44-47] in 2020, as follows:

- Urban residential and non-residential building-generated aggregate waste has an 8% recycling rate, with 60% re-entering the building's construction cycle and 40% being downcycled for infrastructure use. The unrecycled fraction is managed with 10% comprehensive use as fillings and 90% being landfilled.
- Rural residence-generated aggregate waste has a 5% recycling rate, with the recycled portion similarly allocated between housing construction and infrastructure downcycling. The entirety of the non-recycled waste is directed to landfills.
- Aggregate waste from pipelines and waterworks sees a 15% recycling rate for self-use, with the remainder landfilled.

- Aggregate waste from highways, urban and rural roads, railways, rail transit, parks, etc. has a 40% recycling rate. Of this, 80% is recycled, and 20% is used for filling, with non-utilized portions being landfilled.
- Rural road-generated aggregate waste has a 10% recycling rate for self-use. Non-recycled waste is landfilled.
- Aggregate wastes generated by building sublayers and road sublayers have an 80% recycling rate for self-use, and the remainder is landfilled.
- Construction waste aggregates have a 5% recycling rate, with 20% contributing to buildings and 80% to infrastructure. Non-recycled portions are managed with 20% fillings and 80% landfilled.

2.3.2 Natural Sand and Gravel

Mining of natural sand and gravel has significant environmental impacts within the industry. Currently, China's supply of aggregate resources has transitioned from natural sand and gravel to crushed stone. In line with the policy trends of China's aggregate industry, there will be a further reduction in reliance on natural sand and gravel, potentially limiting the use of dredged sand as the sole natural source in the future[48,49].

In this study's scenario setting, the use of natural sand and gravel on the supply side is minimized. The limited demand for aggregates in China before and after the reform and opening-ups, and the absence of severe environmental impacts from natural sand and gravel mining, support this approach. Additionally, the long-term sediment transport by rivers indicates a natural replenishment of sand resources. Based on the metabolic analysis of national sand and gravel resources in our previous study[16], China's supply of natural sand and gravel in 1978 was 1.306 billion tons. The "China River Sediment Bulletin" reports that the sediment transport volume of China's major rivers and the Qinghai Lake area in 2020 was 477 million tons, with a multi-year average of 1.45 billion tons. Based on this data, this study projects a future scenario where the national supply of natural sand and gravel decreases from the current 3 billion tons to an average of 1.5 billion tons for 2021-2035, and then to 1.306 billion tons for 2036-2050. This approach aims to reduce dependence on natural sand and gravel and mitigate environmental impacts.

This study focuses on the national-level supply of natural sand and gravel, without delving into provincial-level supplies, due to variations in resource endowments and hydrological environments across different regions.

2.3.3 Crushed stone

Crushed stone production primarily originates from row rock mines and includes the comprehensive use of tailings and waste rock. This segment offers a more autonomous and flexible supply for various types of aggregate resources. Due to the high level of industrialization and its significant share in the supply side, crushed stone have a substantial impact on the development of the aggregate industry.

This study has assessed future aggregate inflow through demand-side scenario analysis and determined the future supply of recycled aggregates and natural sand and gravel through supply-side scenario analysis. According to the principle of conservation of matter, the future supply of manufactured aggregates is calculated by adding the losses from processing and construction activities to the projected aggregate inflow and then subtracting the future supplies of recycled aggregates and natural sand and gravel.

2.4 Scenario Settings and Evaluation

2.4.1 Demand-Side

As delineated in the scenario analysis framework (Figure S5), this study on the demand side formulates scenarios for intensive use and lightweight design, grounded in the "Reduce" aspect of the circular economy's "3R" principle. Additionally, a lifetime extension scenario is developed based on the "Reuse" principle, aiming to diminish the demand for aggregate resources.

In the intensive-use scenario, the focus is on curbing the growth of stocks in buildings and transportation infrastructure, which are significant consumers of aggregates. The strategy involves maximizing the use of existing stocks to lessen the demand driven by these end uses. Reducing building stock growth is also pivotal for energy conservation and emission reduction during both the construction and operational phases. Drawing from relevant literature[43,50] and construction standards[26,28], this scenario proposes a 20% reduction in the saturated stocks for various building types, highways, and high-speed railways, and a 10% reduction for general-speed railways, as per the model's parameter settings.

The lightweight design scenario contemplates diminishing the per-unit volume demand for aggregates across various end uses through technological advancements and product design optimization[51] (e.g., hollow concrete structures), thereby reducing overall consumption[39]. For this scenario, the study posits a gradual decrease in the material intensity of aggregates for buildings, averaging a 10% reduction from 2021 to 2050 relative to the 2020 baseline.

In the lifetime extension scenario, the aim is to prolong the service life of end uses, ensuring optimal utilization and value realization during their operational phase. The service lifespan of residential buildings in China has traditionally been much shorter than that in developed economies[1], typically ranging from 30 to 40 years. With the shift towards high-quality development, there is a reduced likelihood of significant demolition and reconstruction activities, favouring the extension of the existing stock's service life. This study assumes a 90% extension in the service life of new building constructions from 2021 to 2050, based on the 2020 benchmark. Additionally, houses completed between 2000 and 2020 are projected to have a 30% extended service life over their original expectancy. This study assumes a 60% extension in the service life of new infrastructure constructions from 2021 to 2050, based on the 2020 benchmark. The standard deviation is still 30% of the expected lifetime.

2.4.2 Supply-Side

In alignment with the scenario analysis framework depicted in Figure S5, the supply side of this study introduces an improved recycling scenario, rooted in the "Recycle" component of the circular economy's "3R" principle. This scenario envisions a prospect in the future recycling rates of aggregate waste, alongside the supply dynamics of recycled aggregates. The dual objectives are to mitigate the environmental repercussions of aggregate wastes and to curtail the reliance on primary aggregate resources, thereby addressing the looming sand scarcity.

Within the Improved recycling scenario, the future envisions an escalation in the recycling rates of aggregate waste emanating from various end uses. Reflecting on the historical progression of stock development, the recycling rate for waste from buildings is projected to uniformly ascend to an elevated level between 2021 and 2030. Concurrently, the recycling rate for infrastructure-related waste is anticipated to reach a heightened level uniformly by 2035, with both rates expected to continue their slow, steady climb until 2050.

In the improved recycling scenario, the recycling rate and substitution ratio are determined based on current practices in developed countries and the technological constraints of recycled aggregates (RA). In many European and North American nations, the circular utilization rate of construction and demolition waste (CDW) can reach 70–90%[52], whereas in China no official data exist, and it is generally believed to be below 10–20% [45,47,52].

From a feasibility perspective, Harish et al.[53] indicate that a 25% RA replacement ratio in concrete delivers optimal performance, while further increases can degrade its properties. However, future advancements in RA separation and high-performance superplasticizers could raise this threshold. Based on these considerations, we set a 30% recycling rate for building-derived sand and gravel waste by 2050 in the improved recycling scenario, aligning with the point at which overall demand for sand and gravel nearly matches the waste generated, and the RA substitution ratio also approaches 30%. These assumptions are consistent with prevailing technological feasibility. Here, RA refers to recycled aggregate derived from CDW.

The envisaged recycling rates for aggregate waste stemming from different end uses are detailed in Supplemental Tables S3, S4, and Supplementary Data 1, outlining the prospective recycling rates for various types of construction and demolished waste under the recycling development scenario. This strategic enhancement of recycling rates is instrumental in fostering a more sustainable aggregate supply chain, reducing environmental strain, and ensuring a more judicious use of finite aggregate reserves.

3. Extended Discussion

3.1 Definition of Aggregates in the literature

Aggregate resources, due to their extensive distribution and low per-unit value, have historically been overlooked. The definitions of aggregate resources vary domestically and internationally, leading to ambiguity[38,54] and, in some instances, conflation with materials like cement in certain studies[55]. This lack of a clear, standardized definition complicates efforts to uniformly assess the extraction volume, trade volume, and environmental impact of these mineral resources. This study synthesizes various documents, reports, and standards to establish a conceptual definition of China's aggregate resources within the context of this research.

Internationally, aggregate resources are often categorized as non-metallic or construction minerals, yet specific definitions are seldom provided in scholarly literature. The EU Guideline [56] delineates the material flow account of economic systems, classifying sand and gravel under the non-metallic category. This encompasses both industrial and construction sand and gravel, which are extracted directly from the natural environment. Additionally, a distinct category within non-metallic resources includes crushed rock, which refers to machine-made sand and gravel derived from processed stone ores for construction purposes.

Recent literature also touches upon the definition of aggregates. Scholars like John emphasize that the resource characterization of sand is based on its particle size range (0.063 to 2 mm) rather than its chemical composition[54]. Other researchers, including Torres, collectively refer to sand, gravel, and manufactured aggregates[57].

The Global Resource Information Database Project, an initiative by the United Nations Environment Program (UNEP), the Swiss Federal Office for the Environment (FOEN), and the University of Geneva (UniGe) engaged in a comprehensive discourse on aggregates, releasing reports on sustainable development paths for these resources and deliberating on their definitions[38,58]. Drawing from the International Organization for Standardization (ISO), the American Society for Testing and Materials (ASTM), and the Eurasian Committee for Standardization, Measurement, and Certification (GOST), it is evident that definitions of aggregates vary across different industries and regions, with conceptual overlaps among soil, sand, and stone. As illustrated in Table S5, this study consolidates various sources and expert insights to outline the primary terms and definitions relevant to aggregate resources. In addition, the term "crushed stone" (or "crushed rock") is frequently encountered in existing reports and literature[56,59].

Experts from UNEP/GRID-Geneva[60] have conducted an extensive analysis of the definition of aggregates, considering both the sources and applications of these materials. From the source perspective, distinctions are made between crushed stone derived from the mining and processing of stone, natural sand, and gravel from rivers, sea, lakes, and pits, as well as industrial tailings and waste rock, recycled aggregates, and dredged sand. Notably, river, sea, lake, and pit sand are collectively categorized as naturally-occurring sand and gravel. Currently, natural sand and gravel are predominantly recognized as the principal sources of these resources globally.

In terms of application, aggregates are segmented into categories such as construction, industrial, agricultural, and ecological restoration usage. The primary focus tends to be on construction aggregates and industrial sand and gravel, although there is some conflation between these two categories in certain documents. Agricultural and ecological restoration sand and gravel, being less common applications, are not emphasized in this study.

In 2018, with China's aggregate demand surpassing supply and the environmental repercussions of sand mining becoming increasingly evident, a surge in research related to China's aggregate resources emerged. Nonetheless, a universally accepted definition of aggregate resources within the academic realm remains elusive. The "China Land and Resources Statistical Yearbook" categorizes these resources based on their applications and mineral types, listing over ten varieties of industrial sand and gravel and approximately twenty types of construction rock mines[61]. The national standards "Sand for Construction" and "Pebble and Gravel for Construction" provide specific definitions for construction-related aggregates (referenced in Table S6). Moreover, recycled aggregates are also recognized as viable sources. The definitions found in the national standards "Recycled Fine Aggregate for Concrete and Mortar" and "Recycled Coarse Aggregate for Concrete" are detailed in Table S7. Following the "Report on Conservation and Comprehensive Utilization of Mineral Resources (2022)", these materials are classified according to standard definitions of coarse and fine aggregates, natural and artificial sand (manufactured sand), and delineated based on their specific construction applications, thus defining their status as mineral resources[62].

3.2 Construction versus Industrial Aggregates

Delineating the categories of construction versus industrial aggregates, existing international statistical frameworks commonly bifurcate aggregates into two distinct classifications: construction sand and gravel, and industrial sand and gravel. According to EU guidelines, construction sand, and gravel encompasses the natural sand and gravel utilized in building activities, whereas industrial sand and gravel comprises specialized varieties such as metallurgical sand, fire retardant sand, glass-making sand, ceramic sand, chemical sand, and filtration sand, among others. This dual classification is similarly observed in the databases maintained by the United States Geological Survey (USGS) and the British Geological Survey (BGS).

In line with the international demarcation of industrial sand and gravel, the "China Land and Resources Statistical Yearbook" enumerates over ten types of industrial sand and gravel employed in the manufacture of metallurgy, fertilizers, cement, and so forth, alongside approximately twenty variants of construction sand and gravel.

The primary utility of industrial sand and gravel lies in their industrial or ancillary applications, often leveraging their inherent hardness or silicon content. Conversely, construction sand and gravel exploit their robust physical properties for building and construction purposes, predominantly composed of carbonates and silicates without stringent chemical composition specifications. This distinction underscores the fundamental differences in their natural characteristics and specific uses, despite their superficial similarity.

The global discourse on aggregates primarily accentuates its demand and extensive extraction rates, contrasting the production volumes of industrial versus construction sand and gravel. As depicted in Table S9, in most developed nations, industrial sand and gravel represent a mere fraction of the total sand and gravel output, accounting for roughly 1%. Notably, in the United States, the unique context of shale oil and gas extraction necessitates 87 million tons out of 121 million tons of industrial sand for hydraulic fracturing purposes, constituting 70% of the industrial sand segment and driving its predominant consumption.

Compiling various statistical categories related to industrial sand and gravel as presented in the "China Land and Resources Statistical Yearbook" (Table S8), the production volume of industrial sand and gravel in 2015 stood at 48.2557 million tons[61], equating to merely 0.2% of that year's total consumption of construction aggregates[63]. This disparity highlights the significantly lower production and demand for industrial sand and gravel compared to their construction counterparts, devoid of the ecological and supply shortage issues prevalent in the extensive mining of construction aggregates. Consequently, industrial sand and gravel do not align with the focal research questions and objectives of this study.

Moreover, a notable disparity exists in the pricing of industrial versus construction sand and gravel, largely attributable to their intrinsic natural properties and distinct applications. Data from the USGS in 2018 indicates that in the United States, the cost per ton for construction sand and gravel was $9.09, while industrial sand and gravel commanded a significantly higher price of $56.55 per ton[64]. This price difference further underscores the specialized nature of industrial sand and gravel, which, despite being technically suitable for construction purposes, hold greater value in other applications. Consequently, the utilization of high-value industrial sand and gravel for routine construction tasks is generally discouraged due to their premium cost and specialized characteristics.

In essence, industrial sand and gravel are fundamentally distinct from construction sand and gravel in terms of both properties and applications. The current global focus predominantly lies on construction aggregates, driven by concerns over resource scarcity, environmental impacts, and the extensive demand in construction activities, which are not directly related to industrial sand and gravel. Additionally, the socio-economic drivers and social metabolism characteristics of industrial sand and gravel differ markedly from those associated with construction aggregates.

Therefore, in alignment with the primary focus of this study, the model construction and analysis were exclusively dedicated to examining construction aggregates, considering their pivotal role in addressing the pressing issues of resource depletion and environmental consequences.

3.3 Natural Aggregates versus Manufactured Aggregates

Natural sand and gravel constitute the primary materials currently utilized in construction worldwide, with international discourse historically centring on the ecological repercussions of sand mining and the scarcity of these resources. In contrast, recent years have witnessed a significant surge in the adoption of manufactured aggregates in China[16,65], derived predominantly from the mining and processing of ores. International bodies, including the United Nations Environment Programme (UNEP), have advocated for the substitution of traditional natural sand and gravel with manufactured alternatives to mitigate the crisis surrounding sand and gravel resources. Consequently, manufactured aggregates have emerged as a principal source of supply within the Chinese market.

Technical assessments reveal that manufactured aggregates (crushed stone) are fully capable of meeting the requisite standards to replace natural sand and gravel in construction applications. This shift not only secures the ongoing availability of essential aggregates but also contributes to the conservation of natural sand and gravel reserves, curtailing the environmental degradation associated with the extraction processes from rivers and lakes.

3.4 Scope of Study and Aggregates Resources Defined in this Study

In light of the conceptual analysis undertaken, it is evident that there is yet to be a consensus within the Chinese academic community regarding the definition of aggregate resources. Although there is no universally accepted international definition, the scope of definitions tends to be broadly aligned. For this study, the focus is explicitly on construction-related aggregate resources, with a primary emphasis on the context within China. Drawing from the national standard [66] about construction aggregates[67,68], and integrating definitions related to recycled aggregates, this research adopts a comprehensive definition based on a review of relevant literature[48,49,56] and expert consultations. Accordingly, aggregate resources are characterized as non-metallic minerals used in construction, encompassing river sand, lake sand, mountain sand, sea sand, pit sand, pebbles, construction rocks, tailings, waste rock, and construction waste.

As depicted in Figure S1, the definition of aggregate resources within this study is twofold, encompassing both resource and material attributes. From a resource attribute perspective, aggregates possess unique classifications not strictly bound by chemical compositions, yet the mineral resources they comprise may possess distinct chemical properties. This includes primary resources such as river sand, lake sand, mountain sand, desalinated sea sand, and primary construction rock mines, as well as secondary resources like tailings, waste rock, and construction waste. Notably, primary construction rock minerals, which constitute a significant portion of consumption, include approximately twenty mineral types such as construction limestone and basalt, as listed in Table S8.

Regarding material attributes, aggregates serve as intermediary products within the construction industry's supply chain, bridging primary minerals and their end-use applications. The distinction between fine aggregates and coarse aggregates is determined by particle size, with a demarcation at 4.75mm, while building material standards and practical applications impose additional criteria such as gradation, grain shape, and silt content, which influence the classification and quality of these resources.

This study's methodology, informed by the social metabolism of aggregate resources within the economic system and aligned with China's statistical framework, primarily utilizes statistical data on the final use of aggregate resources, such as in buildings and road construction, as foundational data. The specific end-use categories considered are detailed in Table S1.

3.5 Natural Reserves of Aggregate resources Within the Earth's Crust

Drawing from the UNEP IRP Panel data, the extraction of non-metallic minerals utilized in construction globally, spanning from 1970 to 2019, reached 1112.7 gigatons (Gt), with aggregates representing a substantial fraction of this figure. Given the Earth's total land surface of approximately 148.21 million square kilometres and assuming aggregate resources have a density of 2 tons per cubic meter, it is deduced that the volume of aggregate resources extracted over the last five decades could form a layer of approximately 3 to 4 millimetres thick across the entire land surface of the planet.

It's important to note that this calculation takes into account the total land area of the Earth, rather than just the regions that are habitable or utilized for human activities. Therefore, when recalculating this figure to consider only habitable land areas, the resultant layer of aggregates would be significantly thicker than the initially estimated 3 to 4 millimetres, underscoring the vast scale of aggregate extraction over the past fifty years.

3.6 Provincial Peak Dynamics

Regions with underdeveloped economies have not yet reached their peak development, but as China as a whole transitions to a new stage of development and approaches national-level peak targets, these regions are also nearing their peak.

Guangdong Province has not yet peaked primarily due to lower demand for housing construction, as there remains room for growth in housing stock. The reason for this lower demand in Guangdong is twofold. On one hand, Guangdong is a large province, but wealth is concentrated mainly in the Pearl River Delta region, particularly around Guangzhou and Shenzhen. The western part of the province is still less developed, and housing stock needs to increase. On the other hand, Guangdong's economic development model plays a role. As discussed in our material footprint studies [69-71], the province follows a consumption-driven growth model with a focus on light industry. As a result, heavy asset investments, such as in real estate, are less prominent compared to other regions that follow an investment-driven model.

By 2020, five provinces had not yet reached their peak aggregate demand: Xizang

(Tibet), Guizhou, Yunnan, Shaanxi, and Guangdong. We categorized the 31 provinces in mainland China into three groups based on their per capita aggregate demand around 2020. The first group, with a demand of 18-25 tons per capita, includes Tibet, Jiangsu, and Zhejiang. The second group, with a demand of 12-18 tons per capita, consists of 12 provinces: Hubei, Fujian, Guizhou, Yunnan, Chongqing, Qinghai, Jiangxi, Xinjiang, Gansu, Anhui, Shaanxi, and Sichuan. The third group, with a demand of 7-12 tons per capita, covers 16 provinces: Beijing, Hunan, Inner Mongolia, Ningxia, Guangxi, Jilin, Shandong, Hebei, Henan, Shanxi, Hainan, Shanghai, Guangdong, Liaoning, Heilongjiang, and Tianjin.

3.7 Interprovincial and International Trade

We did not account for sand and gravel transportation between provinces, mainly because it is primarily transported by road, with a very short transportation radius, generally no more than 50-150 km[54,58], which is much smaller than the radius of Chinese provinces. Therefore, we have ignored inter-provincial transportation.

As for China’s sand and gravel imports and exports, while the volume is not negligible—mainland China indeed exports a significant amount of sand and gravel to Hong Kong—it accounts for less than 1% of the total sand and gravel production/usage in mainland China, so it can be considered insignificant. In recent years, China's net exports of sand and gravel have been around 50 million tons, while domestic consumption is nearly 20 billion tons.

However, in our study, the demand-side analysis is based on various end-uses, calculated from the bottom up, so inter-provincial transportation is not necessary to consider for historical demand. On the supply side, recycled aggregates are primarily sourced from demolition waste within the province’s sand and gravel stock, so inter-provincial transportation is also not needed from the perspective of the source. In future scenarios, the production and use of primary aggregates and the eventual supply of recycled aggregates may involve inter-provincial transportation. However, due to the difficulty in obtaining data on inter-provincial transportation of sand and gravel, and the relatively small transportation radius, the impact on the overall results is minimal, so we chose to ignore it.

Nonetheless, in future policy planning and research, we hope to see sand and gravel transportation extend beyond provincial boundaries. For example, the Yangtze River Delta region could take advantage of its waterways and align sand and gravel transportation with its supply-demand relationships.

3.8. Review of Aggregate Resources Modelling

There is currently a notable lack of quantitative research on aggregate resources, particularly at sub-national scales, which limits our ability to accurately assess the status of these resources. In Tables S13-14, we provide a summary of existing studies in this field. Most research to date has focused on qualitatively identifying the environmental and social impacts of aggregate extraction, without sufficient data to substantiate these findings. Scholars have emphasized the urgent need to establish a robust quantitative framework to support the sustainable development of the aggregate sector.

In industrial ecology, material flow analysis (MFA) is widely used to examine the exchange of resources between natural and economic systems, as well as internal resource flows within economies. Table S14 summarizes the application of MFA in studying societal metabolism, including extended models that analyze metals, non-metals, and aggregates. The methodologies of EW-MFA and d-MFA are well-established in this context.

Through comprehensive industry investigations, we have developed an in-depth understanding of China’s aggregate industry. Leveraging this knowledge, we have incorporated MFA into a quantitative model, constructing the Social Metabolism Model for China’s aggregate resources and its extension, CHAMPS.

3.9 Ore aggregates (tailings and waste rock)

According to present literature and policies, ore aggregates (also referred to as ore-sand) can be defined as tailings and waste rock associated with mining activities. Waste rock refers to the overburden removed during metal mining, while tailings are low-metal-content materials with limited high-value use. Since they share similar characteristics, we group them under the term 'ore aggregates.

Ore-sand can be categorized into two types:

- **Immediately usable materials**: These are directly used to produce manufactured aggregates and can be treated as equivalent to primary aggregates. Policy documents (https://www.gov.cn/xinwen/2019-11/16/content_5452658.htm) support this view. However, the policy’s focus on "conserving natural resources" suggests that while tailings and waste rock are used for aggregates, they differ from primary stone and are more aligned with waste re-utilization efforts.
- **Stockpiled tailings**: These pose environmental risks and can be considered a secondary resource. They may substitute for manufactured aggregates but are not classified as recycled aggregates since they have not previously entered the economic system.

According to the NDRC (https://www.gov.cn/gzdt/2013-04/08/content_2372577.htm), China generates around 1.5 billion tons of tailings annually, with a utilization rate of about 20%. Half of this is used for building materials and the other half for mine backfilling, while only 3% is used for metal recovery. This equates to 100-200 million tons of tailings replacing primary stone in building materials annually, which is significant in volume but represents only about 1% of China’s total aggregate consumption. Given its relatively small impact, we did not address this separately in the model.

However, we have included tailings and waste rock in our calculations. In Figure S3, MF5.1 represents these materials, and they are fully accounted for in the model.

In the future scenarios modelled, we include natural, manufactured, and recycled aggregates as sources. Tailings and waste rock are considered part of the manufactured aggregate system. Although associated with comprehensive utilization, they have not re-entered the extraction system (often already extracted or used for backfilling) and, therefore, do not qualify as recycled aggregates.

While we include ore-sand in the total volume, we cannot provide a detailed analysis of the exact amount of tailings and waste rock used in manufactured aggregates. This is due to the lack of comprehensive statistical data on tailings and waste rock in China. Furthermore, the physical properties of tailings and waste rock may limit their suitability for construction aggregates. For example, some tailings are ground into fine powder during hydrometallurgy, rendering them unsuitable for aggregate use. Others may have high densities, potentially causing issues like building subsidence.

This study does not quantitatively focus on how much tailings and waste rock can replace the primary stone in manufactured aggregate production. In future scenarios, aggregate demand in China is expected to decrease significantly. Even if manufactured aggregates were entirely derived from primary stone, extraction volumes would remain within acceptable limits. Nonetheless, we emphasize the importance of maximizing the use of tailings and waste rock to reduce reliance on primary stone.

China's stockpile of tailings and waste rock is estimated at 60 billion tons (NDRC). However, it remains uncertain how much of this can be used for aggregate production or whether it is suitable for this purpose. If all stockpiled tailings and waste rock were usable, they could replace a significant portion of the primary stone, potentially meeting future demand. However, this assumption is beyond the scope of the current model, and we will continue to engage with industry experts to better understand these materials.

For tailings, the highest value-added use in China is likely metal recovery, as prioritized in national policies. Tailings suitable for metallurgical recovery should be used for that purpose first. Those unsuitable for metal recovery should be used for aggregate production to reduce primary stone extraction. For stockpiled tailings, policies and standards are needed to facilitate their orderly use, thereby minimizing primary stone extraction over the medium to long term. The utilization of tailings and waste rock is a complex issue that requires further research and careful consideration.

3.10 Extended Discussion on Recycled aggregates

Internationally, there has been extensive research on recycled aggregates (RA). Li et al.[52] conducted a review showing that since 2000, more than 60,000 publications on RA have appeared worldwide, with an exponential rise in recent years. This review discusses RA usage, technological challenges, policy gaps, and recommendations for future development.

(1) From a technological perspective, RA differs from primary aggregate mainly due to the residual mortar attached to its surface[72], which weakens the bond between RA and cement, leading to inferior performance compared to primary aggregates[73]. RA surface pore structure[74,75] contributes to inherent defects, including high porosity, high water absorption, and a weakened interfacial transition zone (ITZ). These defects adversely affect the performance of recycled aggregate concrete (RAC), including its compatibility, mechanical properties, and fresh durability[76].

According to Harish et al.[53], a 25% RA replacement ratio yields optimal concrete properties, but higher ratios reduce performance. With further development in RA separation and high-performance superplasticizers, RA replacement ratios could increase. In our improved recycling scenario, we assume 30% of building-derived waste aggregates is reused in building construction by 2050, a technically feasible target.

(2) Regarding cost, RA is generally slightly more expensive than primary aggregates due to more complex separation and screening. One study shows that concrete made with RA can be 0–10% more expensive than that made with primary aggregates[77]. However, both RA and primary aggregates have low unit values compared to other bulk commodities, and costs depend strongly on market structure, availability of raw material sources, and transport distance[78].

A review of publications from 2000 to 2021 identified 35 papers, which list 15 factors that influence RA cost, including sales cost, replacement ratio, water–cement ratio, cement content, supplementary cementitious materials, chemical admixtures, installation fees, RA transport fees, concrete transport fees, quality control measures, indirect costs, mandatory regulations, voluntary guidelines, population growth, and economic growth[77].

(3) Although the RA market remains immature and lacks complete standards, its long-term potential is promising, as RA can reduce environmental impacts and overall waste. In many developed countries, construction and demolition waste (CDW) recycling rates reach 70–90%. In China, the rate is generally assumed to be below 10–20%[45,47,52].

Still, China is advancing rapidly by issuing RA standards (including GB/T 25176, GB/T 25177, JGJ/T 240, JG/T 505, JC/T 2281) and promoting RA industry policies[79-81].

Thirty-five pilot cities have achieved around 50% resource utilization—15 percentage points higher than before the pilot projects—indicating substantial room for growth[47]. Should China reach European, North American, or Japanese recycling levels, the RA market could exceed one trillion RMB[82], representing significant opportunities for further development.

Supplementary Figures

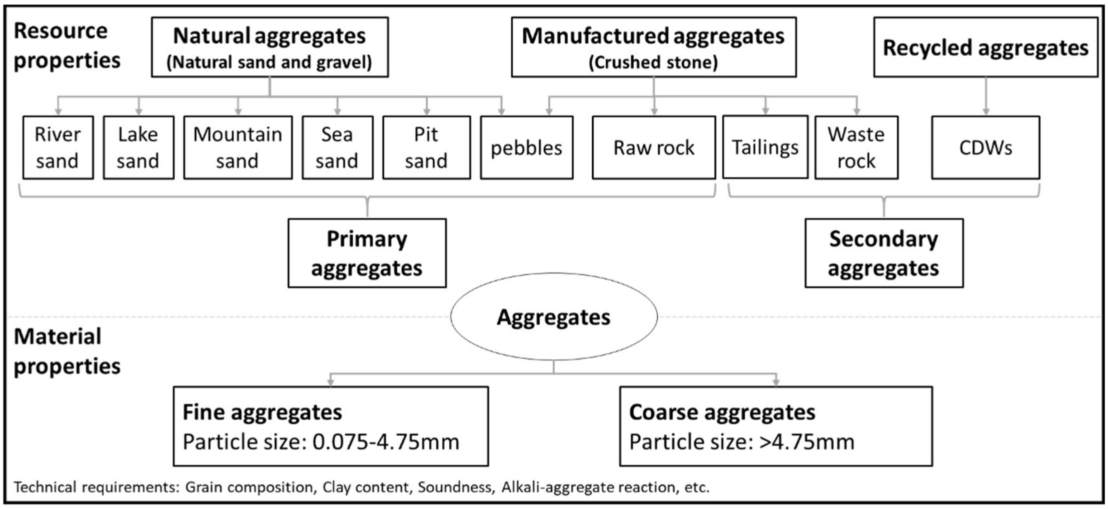

Figure S1 Definition of aggregate resources. The definition of aggregate resources primarily encompasses two aspects: resource properties and material properties. The resource properties mainly include the sources of the aggregates and their classification as primary or secondary resources. The material properties mainly involve engineering-based classifications and technical requirements.

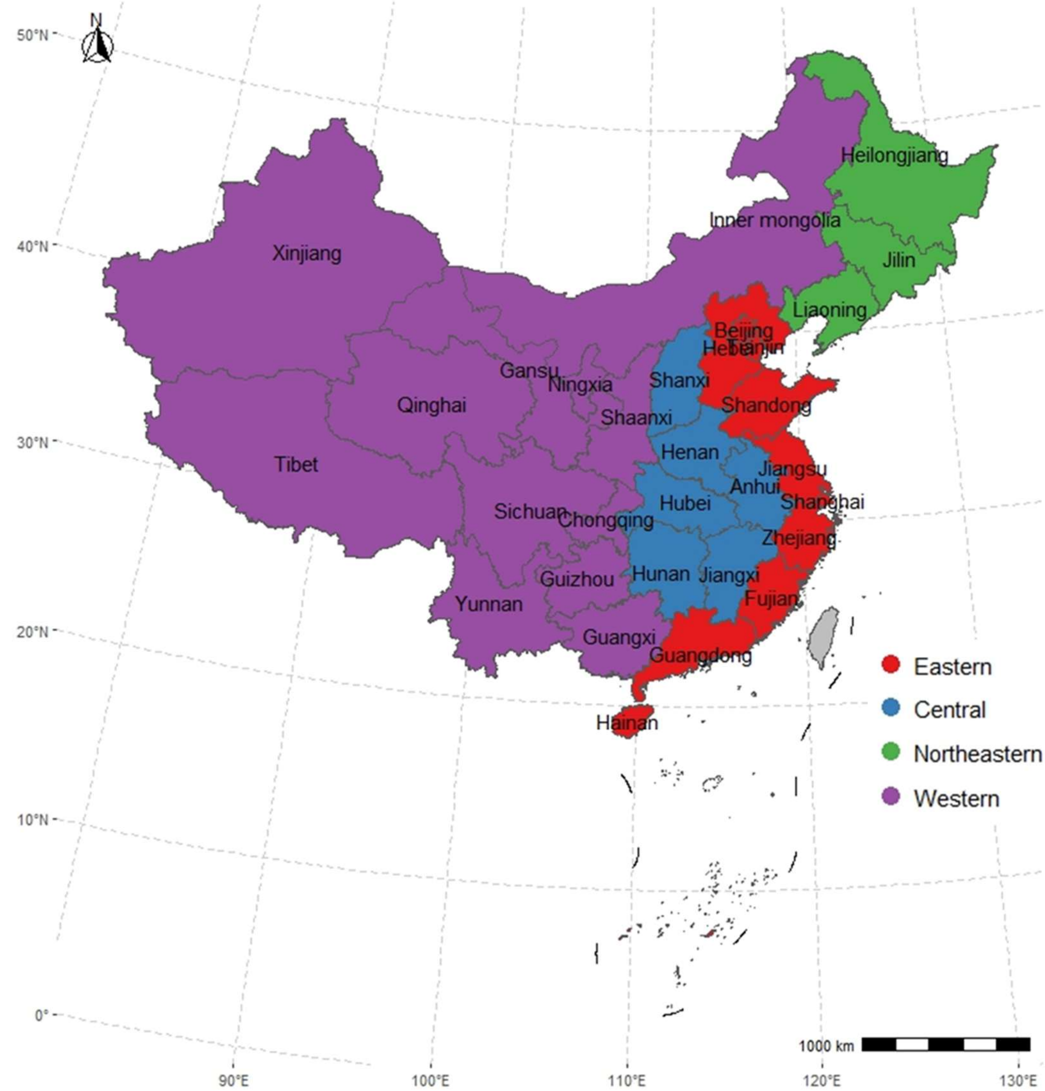

Figure S2 Division of the four major economic regions in China. Different colors represent the regional affiliation of each province: red for the eastern region, blue for the central region, green for the northeastern region, and purple for the western region. The map is produced based on the standard map (Approval No. GS(2024)0650) downloaded from the Standard Map Service website of the China National Administration of Surveying, Mapping and Geoinformation, with no modification to the base map.

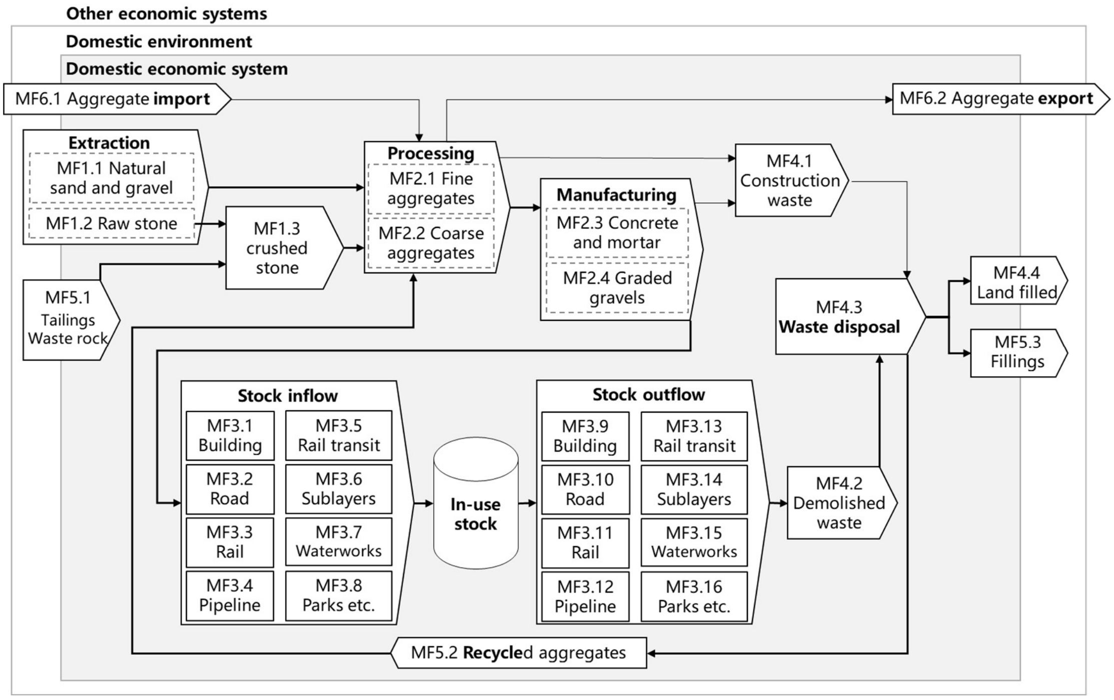

Figure S3 Aggregate metabolism model. This model is constructed based on Economy-Wide Material Flow Analysis (EW-MFA) and Dynamic Material Flow Analysis (DMFA), capturing the flow of aggregate resources within the domestic economic system, as well as between the domestic environment and other economic systems.

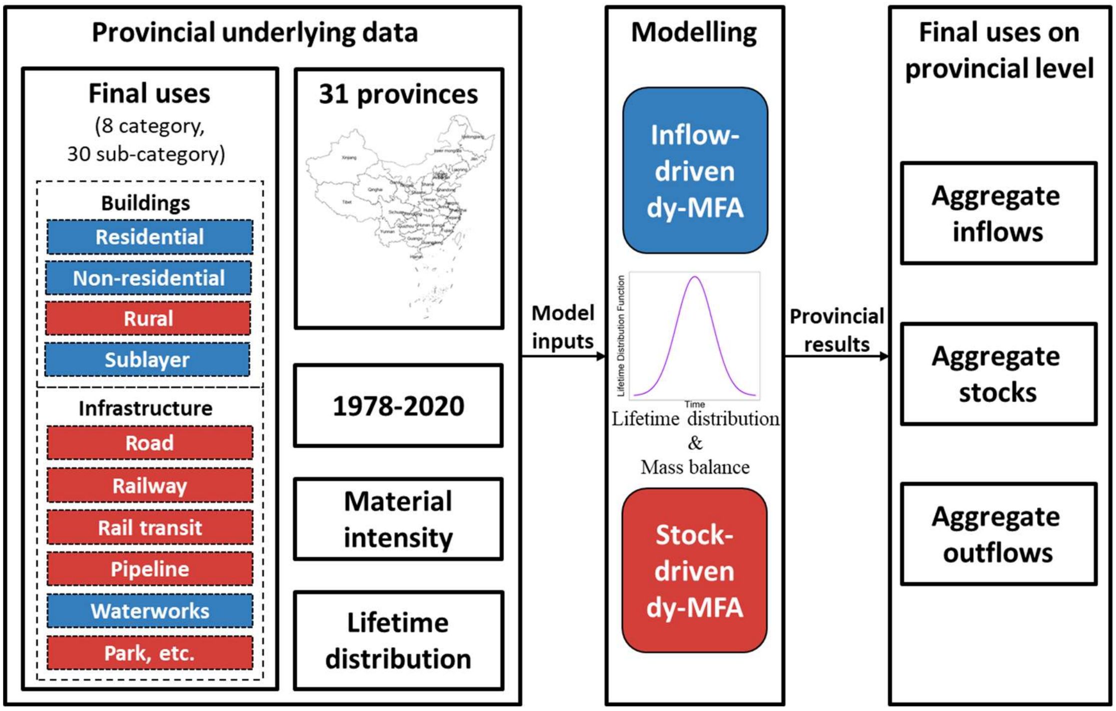

Figure S4 Dynamic material flow analysis model for aggregates at the provincial level (for the historic part of the analysis not for the future scenarios). The colors are used to differentiate between types of dynamic MFA: red indicates stock-driven d-MFA, and blue indicates inflow-driven d-MFA. The combined categories 'Residential,' 'Non-residential,' and 'Rural' refer to 'MF3.1 Building' in Fig. S3. The distinction between historical and future analysis is not relevant to the colors, as this figure only includes the historical data. The map is produced based on the standard map (Approval No. GS(2024)0650) downloaded from the Standard Map Service website of the China National Administration of Surveying, Mapping and Geoinformation, with no modification to the base map.

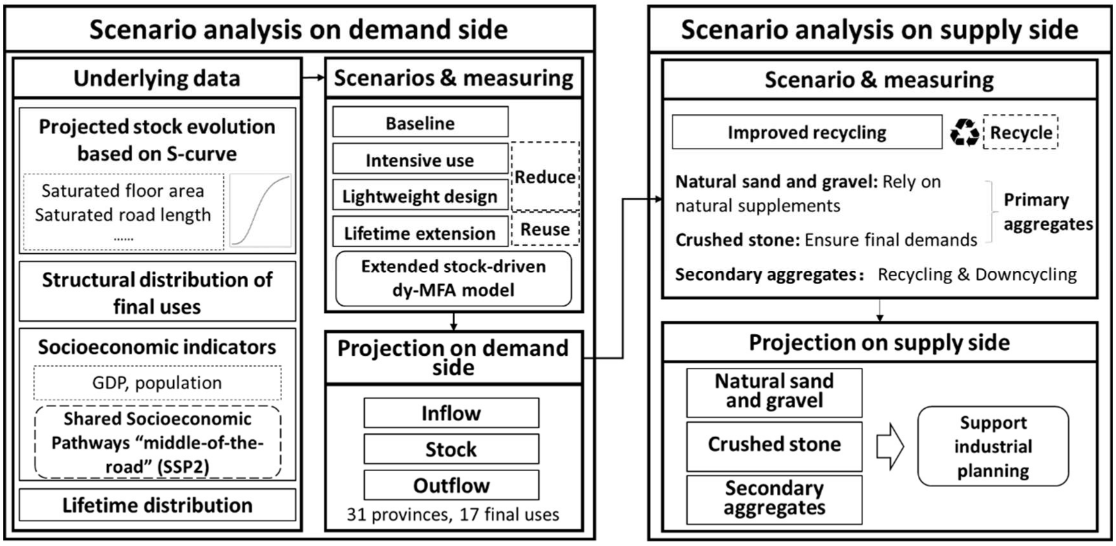

Figure S5 Scenario analysis model for the aggregate resource. The scenario analysis is developed based on potential future circular economy initiatives from both the demand side and the supply side. The left panel illustrates the construction logic of the underlying data and the demand-side scenario measures; the right panel includes supply-side scenario measures and the corresponding calculation logic.

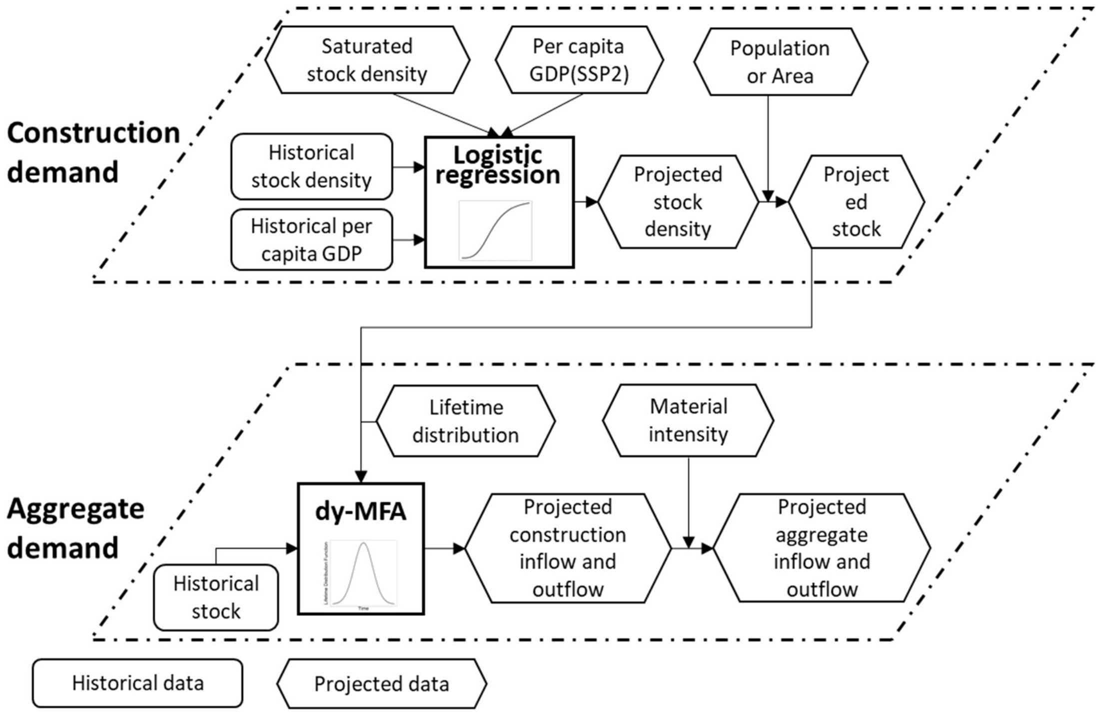

Figure S6 Scenario analysis model on the demand side. The upper section illustrates the methodology for estimating future construction demand, primarily achieved through historical data fitting, future target setting, and logistic curve extrapolation. The lower section presents the approach for estimating future aggregate demand, which is mainly based on projected construction demand and the dynamic material flow model.

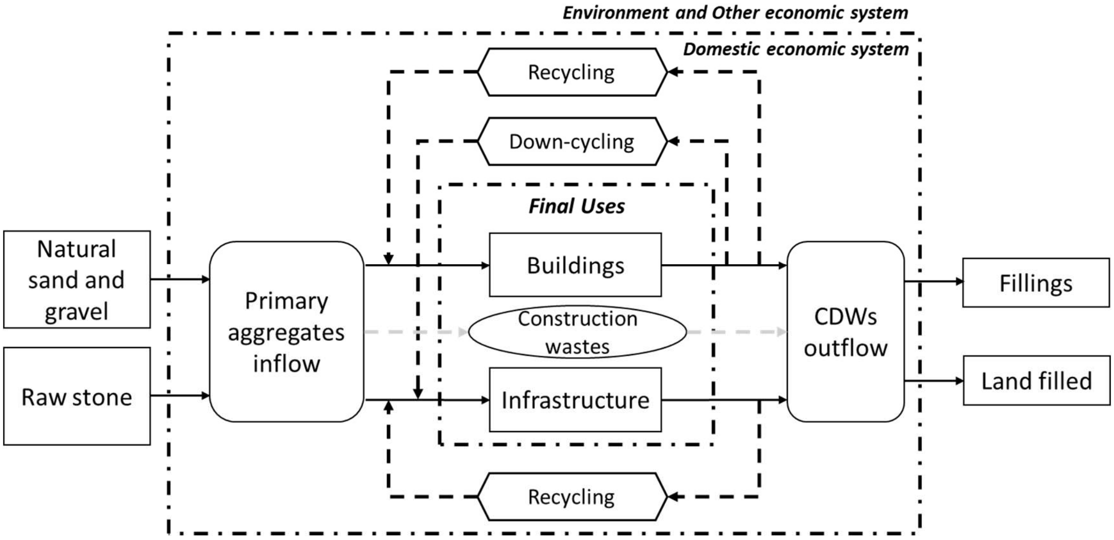

Figure S7 Scenario analysis model on the supply side. This study provides specific definitions for recycling and down-cycling. Recycled aggregates produced through ***recycling*** can be utilized without a reduction in quality. In contrast, recycled aggregates resulting from ***down-cycling*** can only be used in lower-value applications.

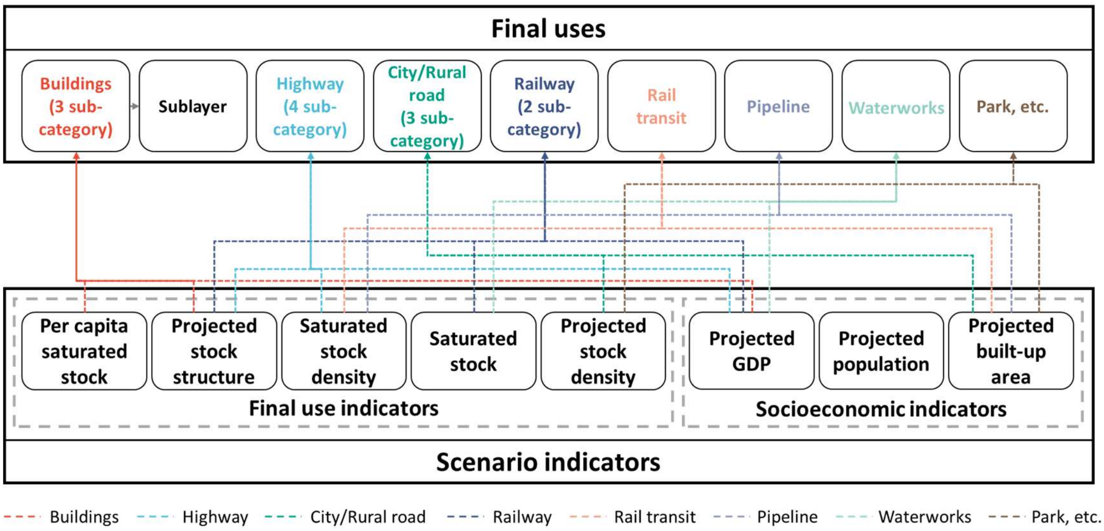

Figure S8 Scenario indicators and corresponding final uses. This figure schematically illustrates the material flow modeling for the scenario component, encompassing 17 final-use categories and the scenario parameters required for their estimation.

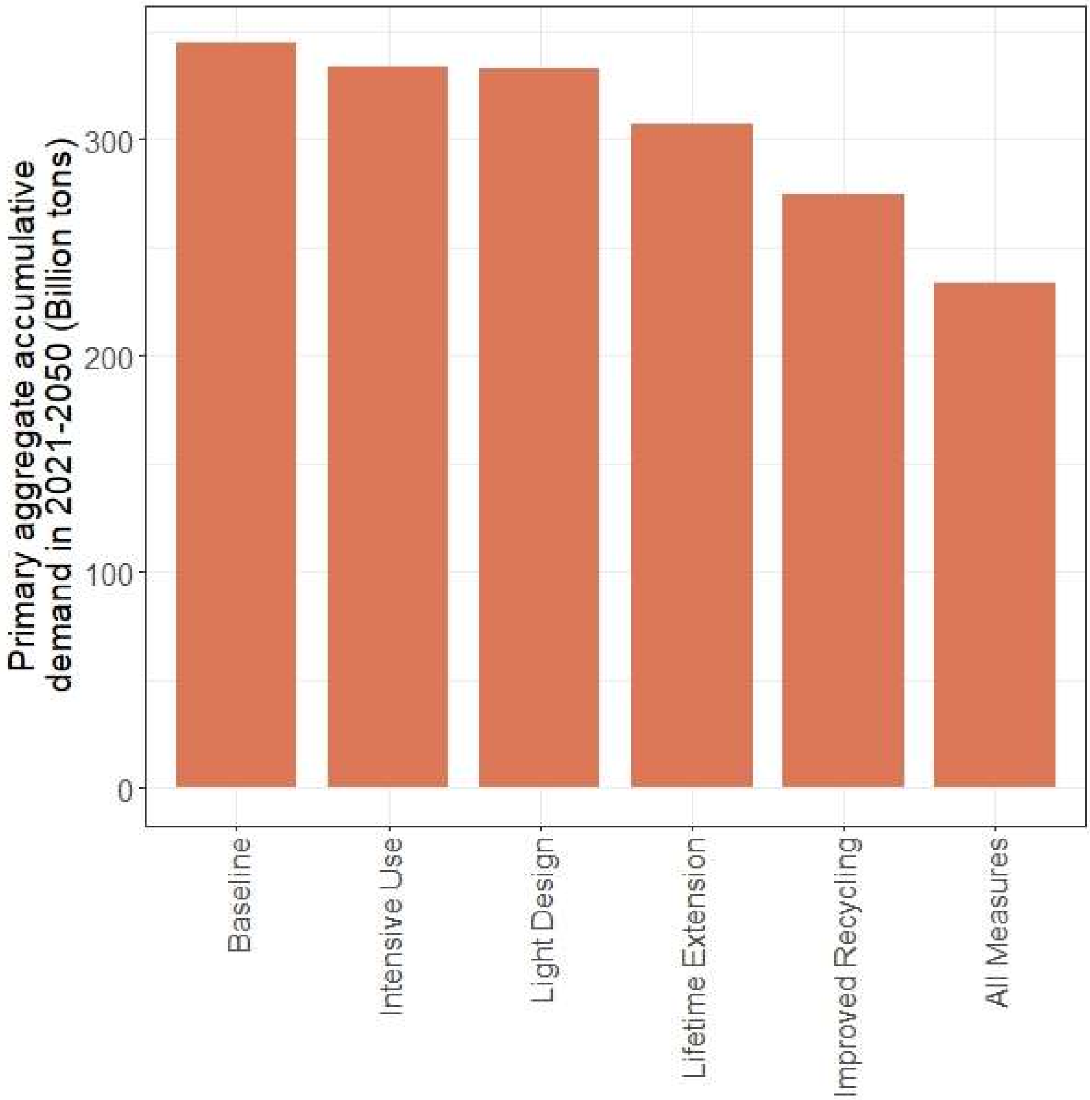

Figure S9 Estimations of accumulative primary aggregate demand from 2021 to 2050 under various Circular Economy (CE) scenarios. This figure shows the cumulative demand for primary sand and gravel in China from 2021 to 2050 under the following scenarios: Baseline, Intensive Use, Lightweight Design, Lifetime Extension, Improved Recycling, and All Measures.

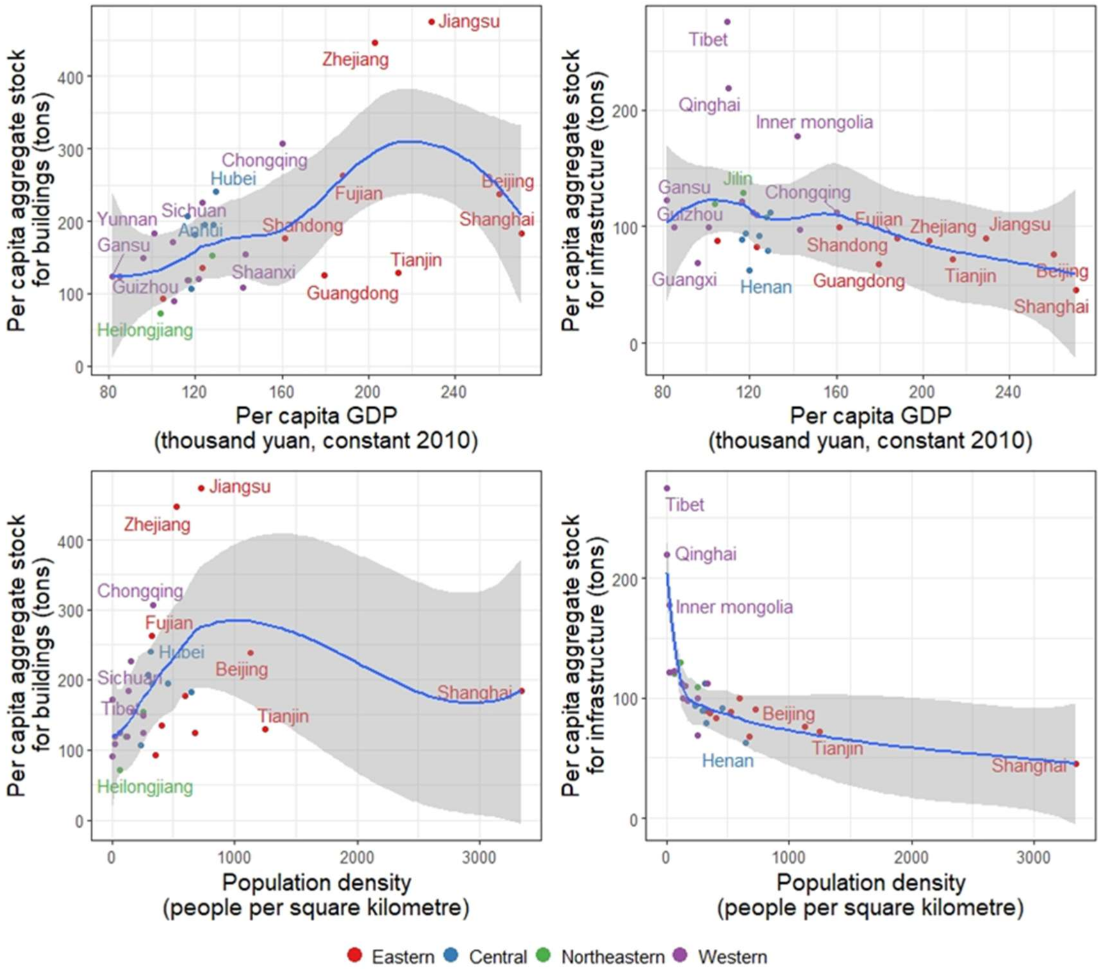

Figure S10 Correlations between population density and per capita GDP with respective aggregate stocks in buildings and infrastructure (2050, All Measures scenario). The color of each province's name corresponds to its respective region in the legend at the bottom of the figure.

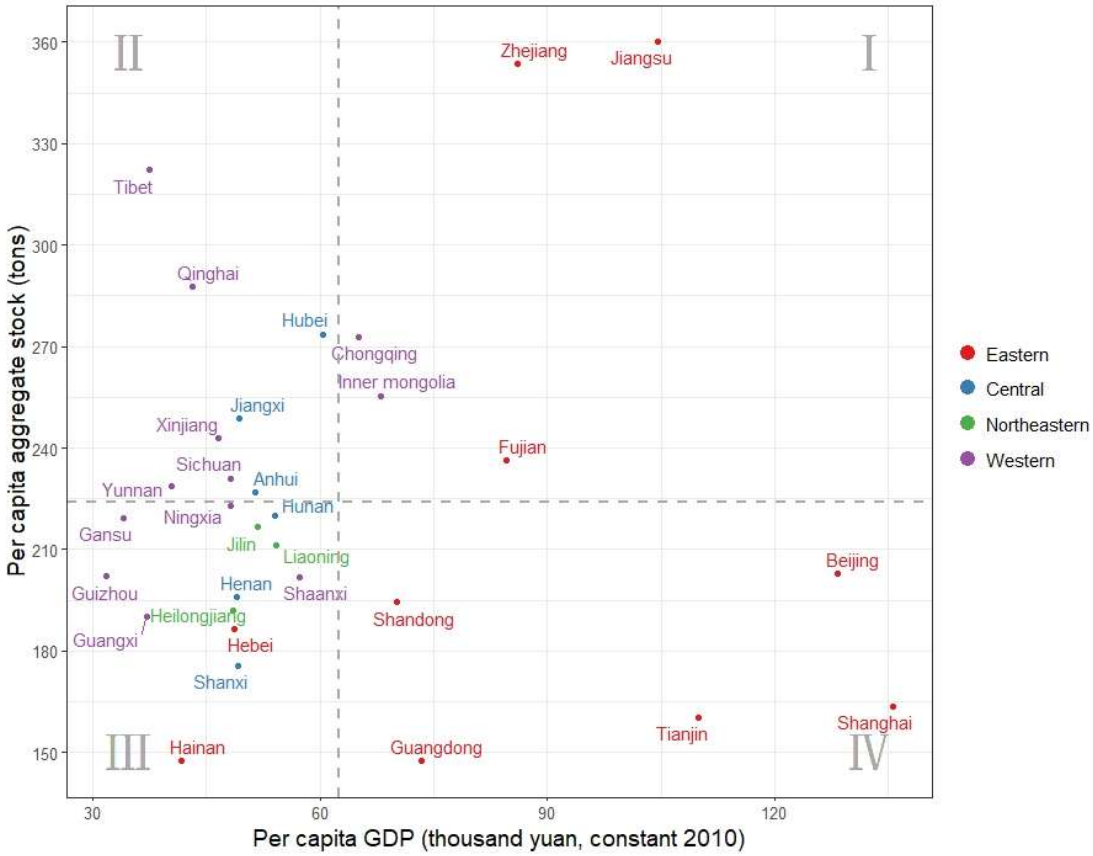

Figure S11 Correlations between per capita GDP with per capita aggregate stock on the provincial level in China (2020). The color of each province's name corresponds to its respective region in the legend on the right.

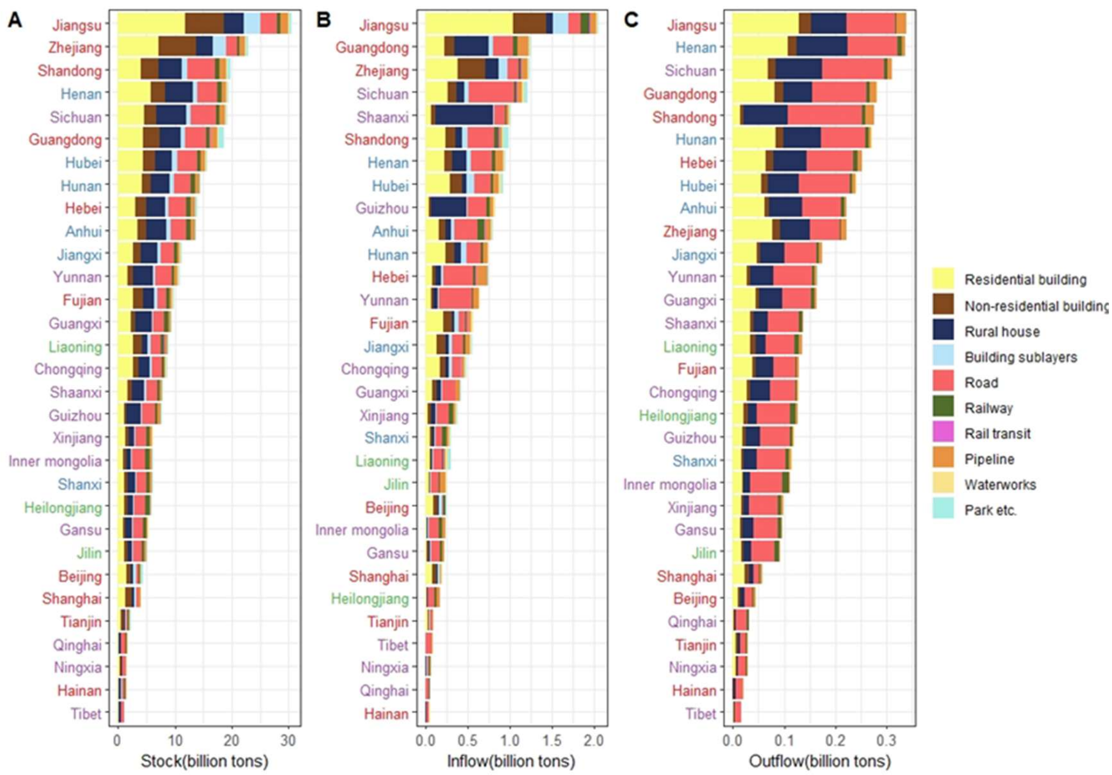

Figure S12 Aggregate stock, inflow, and outflow in provincial China in 2020. The color of each province name on the vertical axis corresponds to its respective region: red for the eastern region, blue for the central region, green for the northeastern region, and purple for the western region.

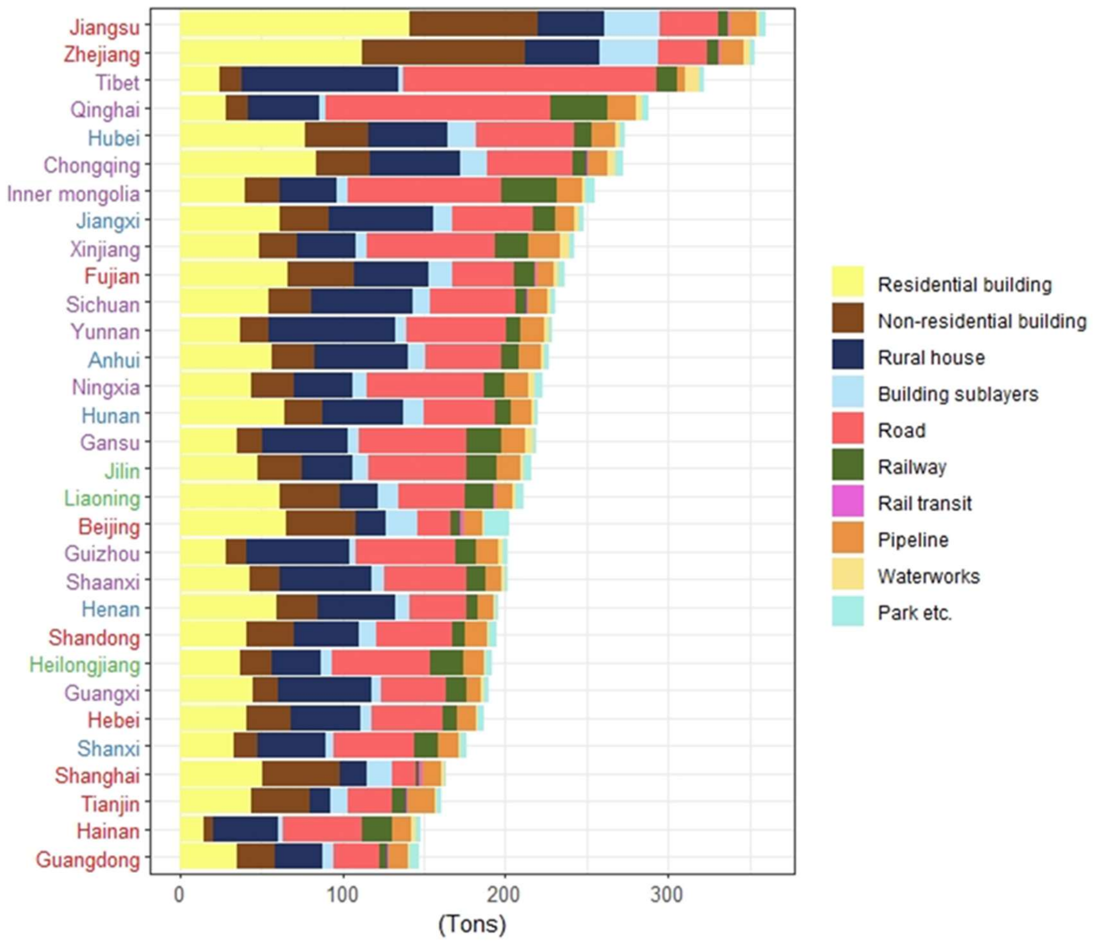

Figure S13 Per capita aggregate stock in provincial China in 2020. The color of each province name on the vertical axis corresponds to its respective region: red for the eastern region, blue for the central region, green for the northeastern region, and purple for the western region.

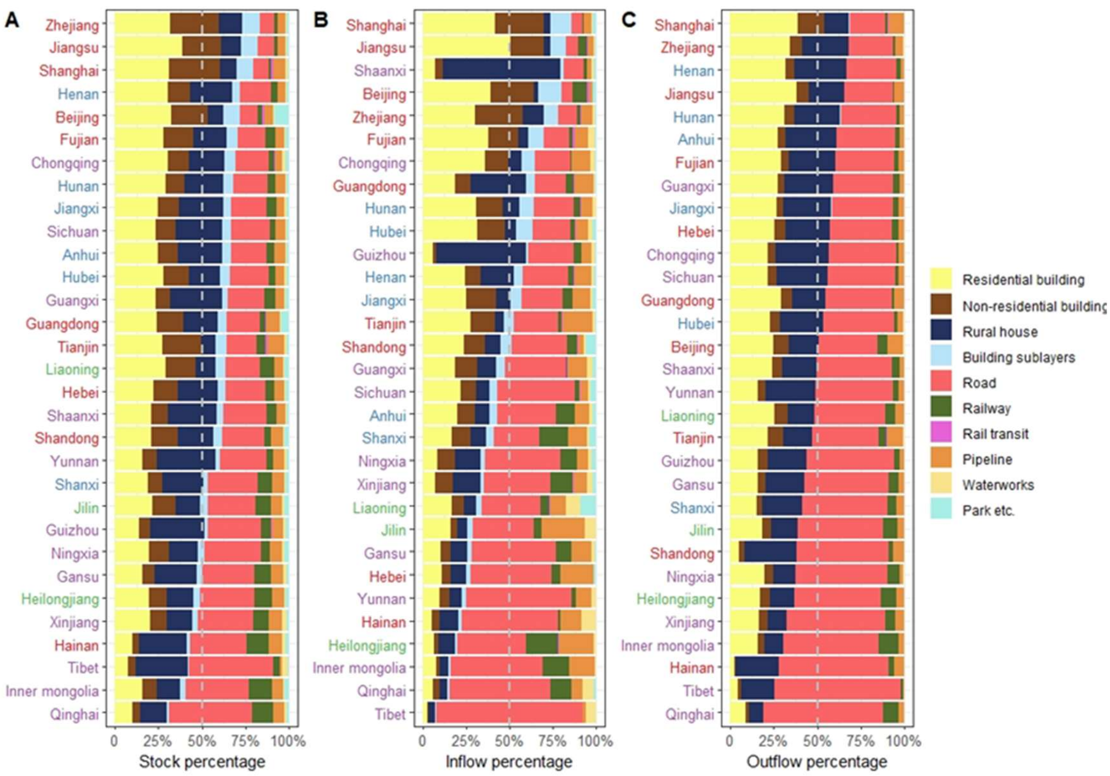

Figure S14 Per capita aggregate stock, inflow, and outflow in provincial China in 2020. The color of each province name on the vertical axis corresponds to its respective region: red for the eastern region, blue for the central region, green for the northeastern region, and purple for the western region.

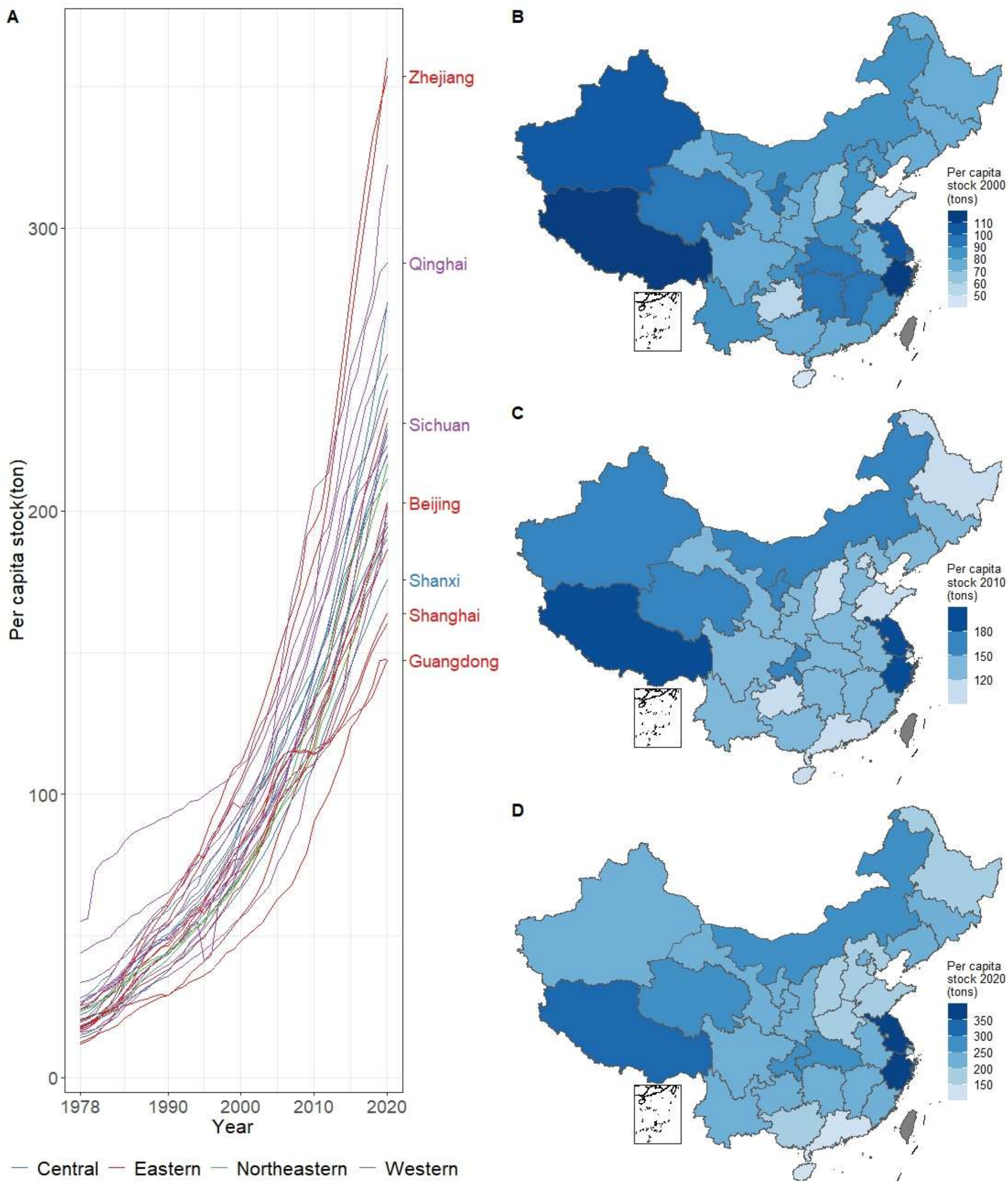

Figure S15 Per capita aggregate stock in provincial China (1978-2020). The maps are produced based on the standard map (Approval No. GS(2024)0650) downloaded from the Standard Map Service website of the China National Administration of Surveying, Mapping and Geoinformation, with no modification to the base map.

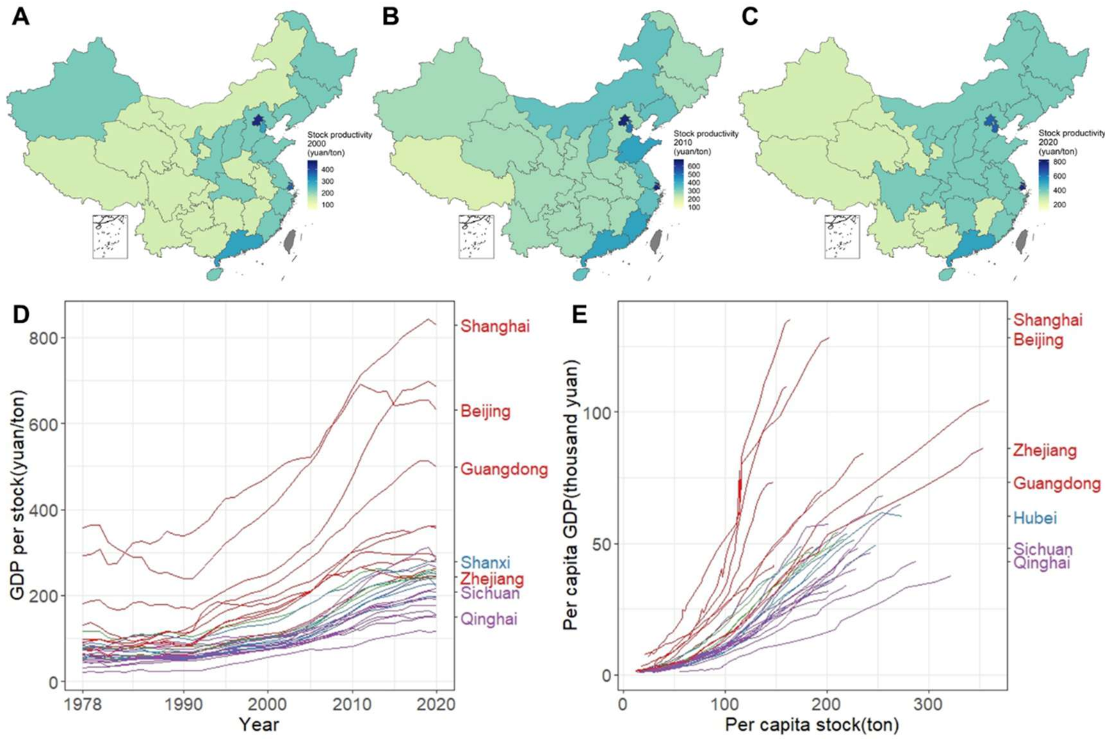

Figure S16 Correlations between aggregate stock and economy in provincial China (1978-2020). The maps are produced based on the standard map (Approval No. GS(2024)0650) downloaded from the Standard Map Service website of the China National Administration of Surveying, Mapping and Geoinformation, with no modification to the base map.

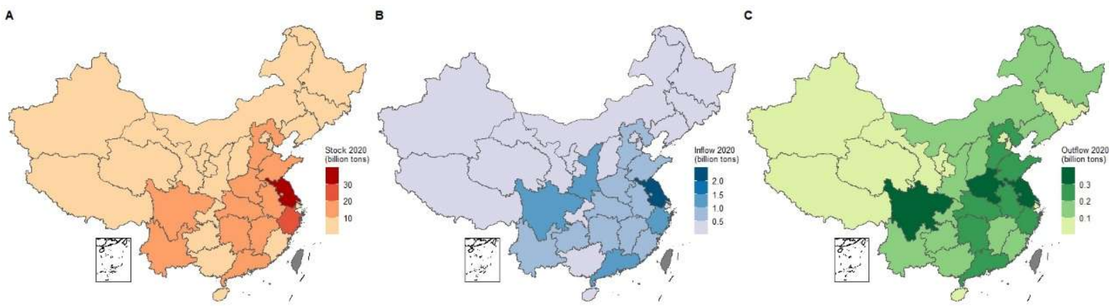

Figure S17 Aggregate stock, inflow, and outflow in provincial China (2020). The maps are produced based on the standard map (Approval No. GS(2024)0650) downloaded from the Standard Map Service website of the China National Administration of Surveying, Mapping and Geoinformation, with no modification to the base map.

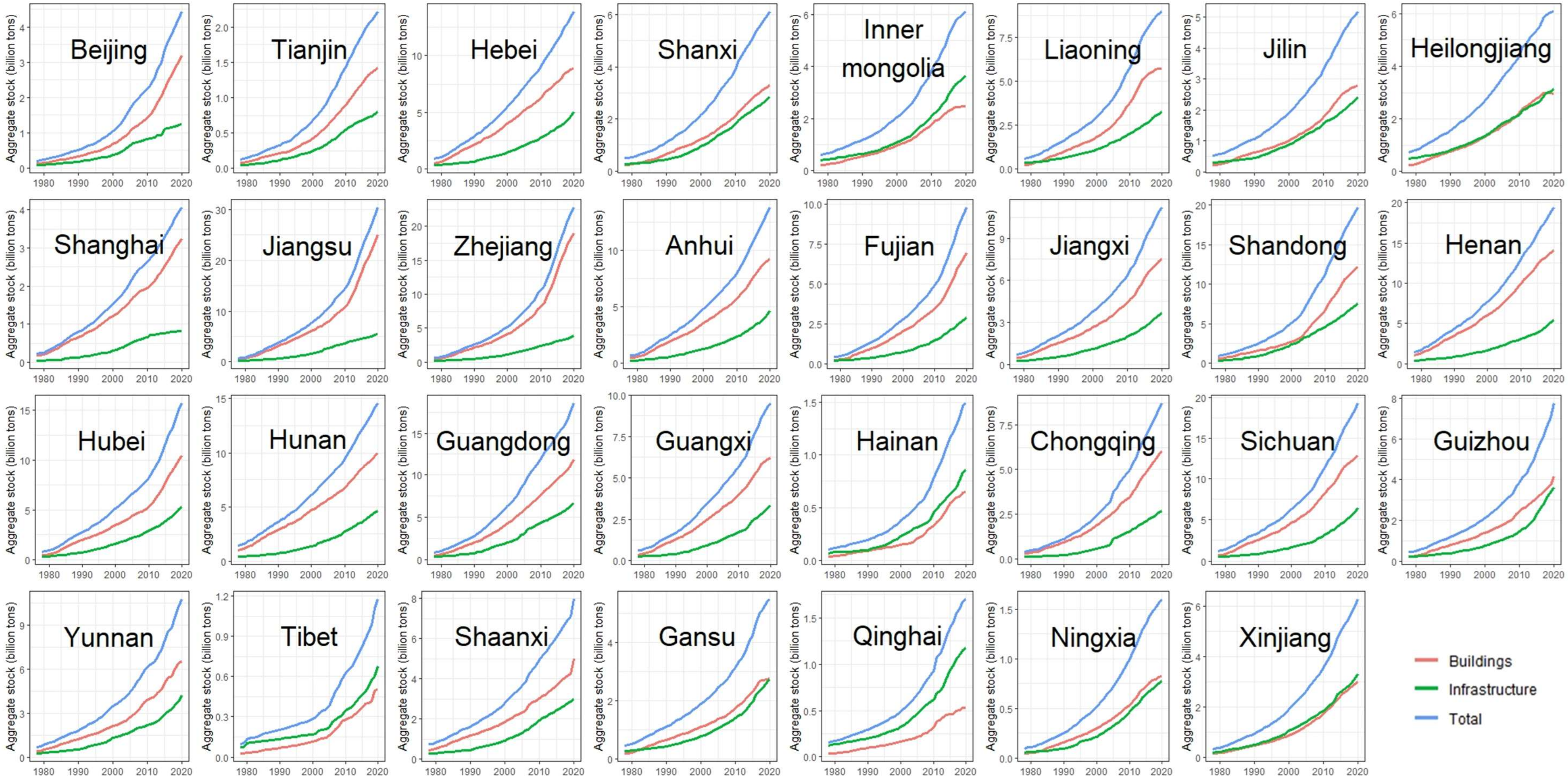

Figure S18 Aggregate stock in provincial China (1978-2020). The stocks are classified by total, buildings, and infrastructure.

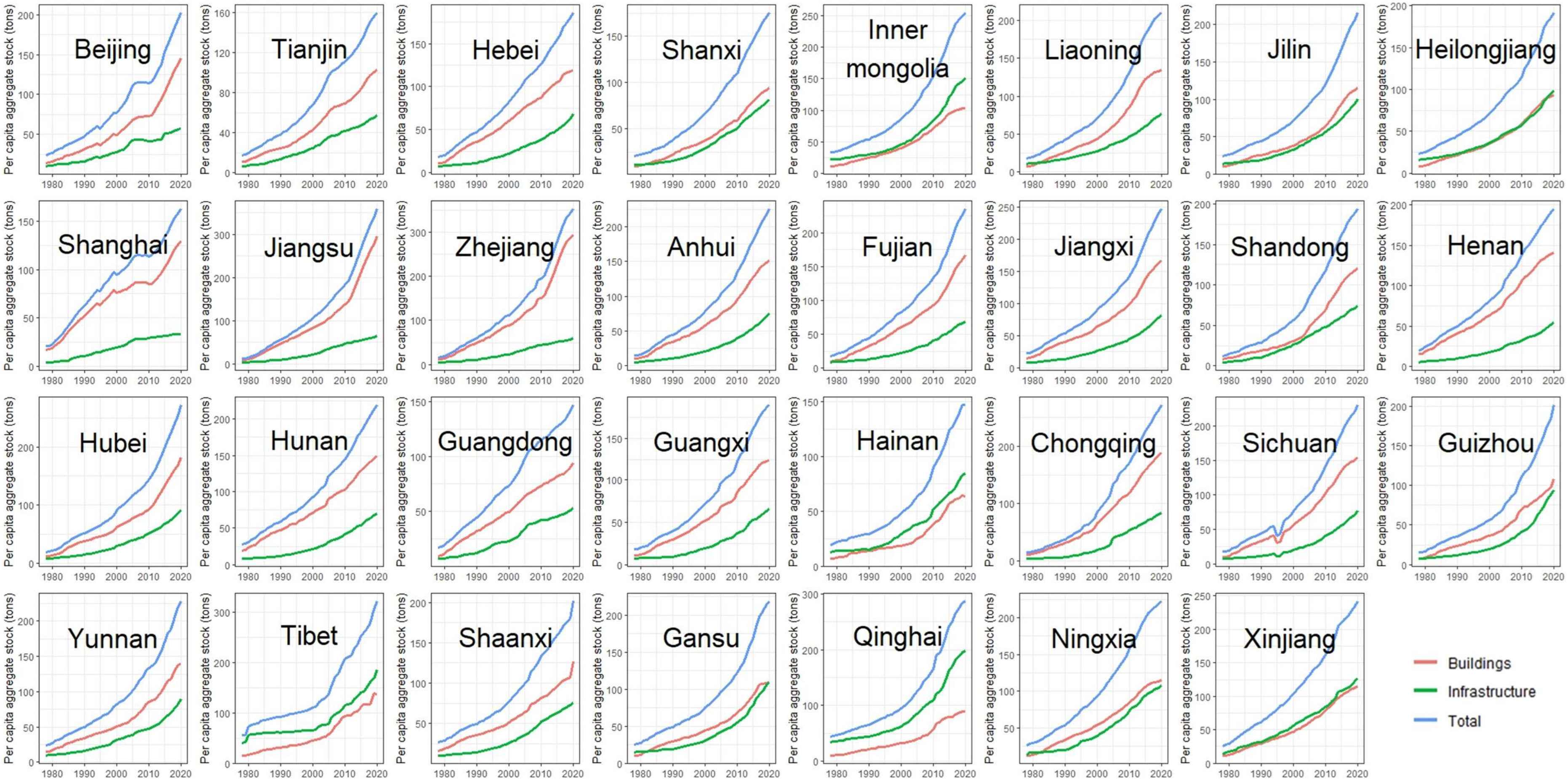

Figure S19 Per capita aggregate stock in provincial China (1978-2020). The per capita stocks are classified by total, buildings, and infrastructure.

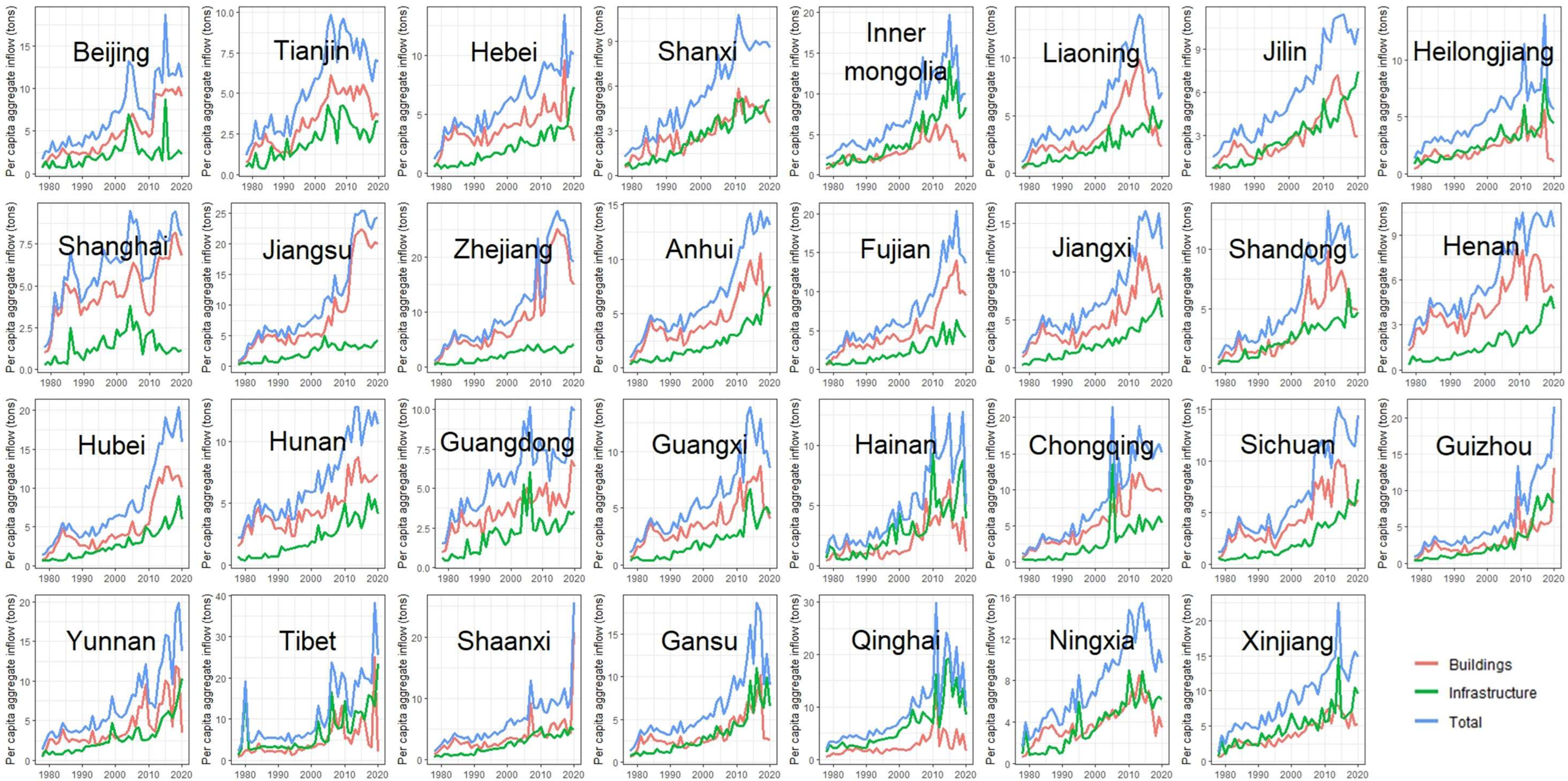

Figure S20 Aggregate inflow in provincial China (1978-2020). The inflows are classified by total, buildings, and infrastructure.

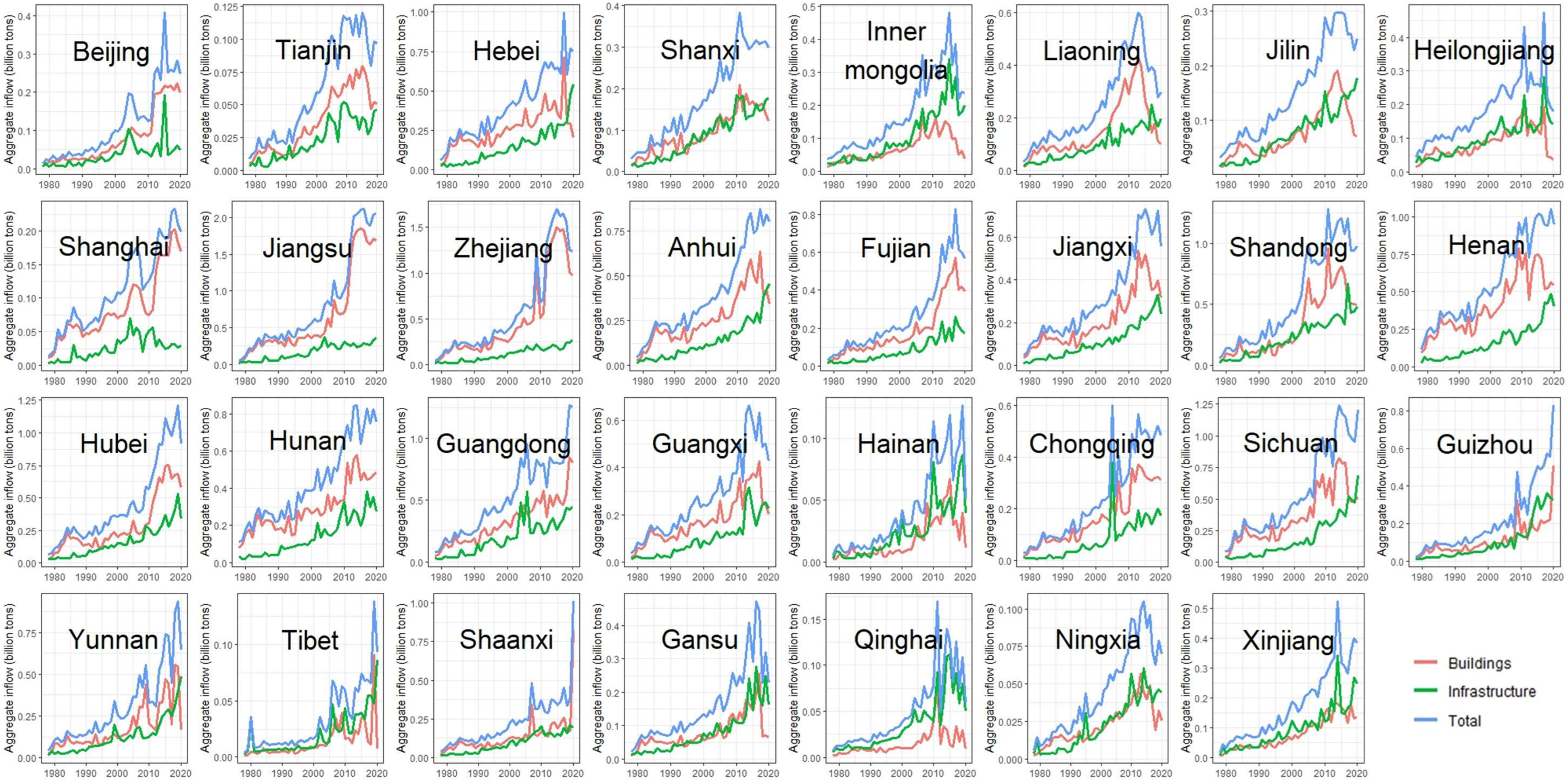

Figure S21 Per capita aggregate inflow in provincial China (1978-2020). The per capita inflows are classified by total, buildings, and infrastructure.

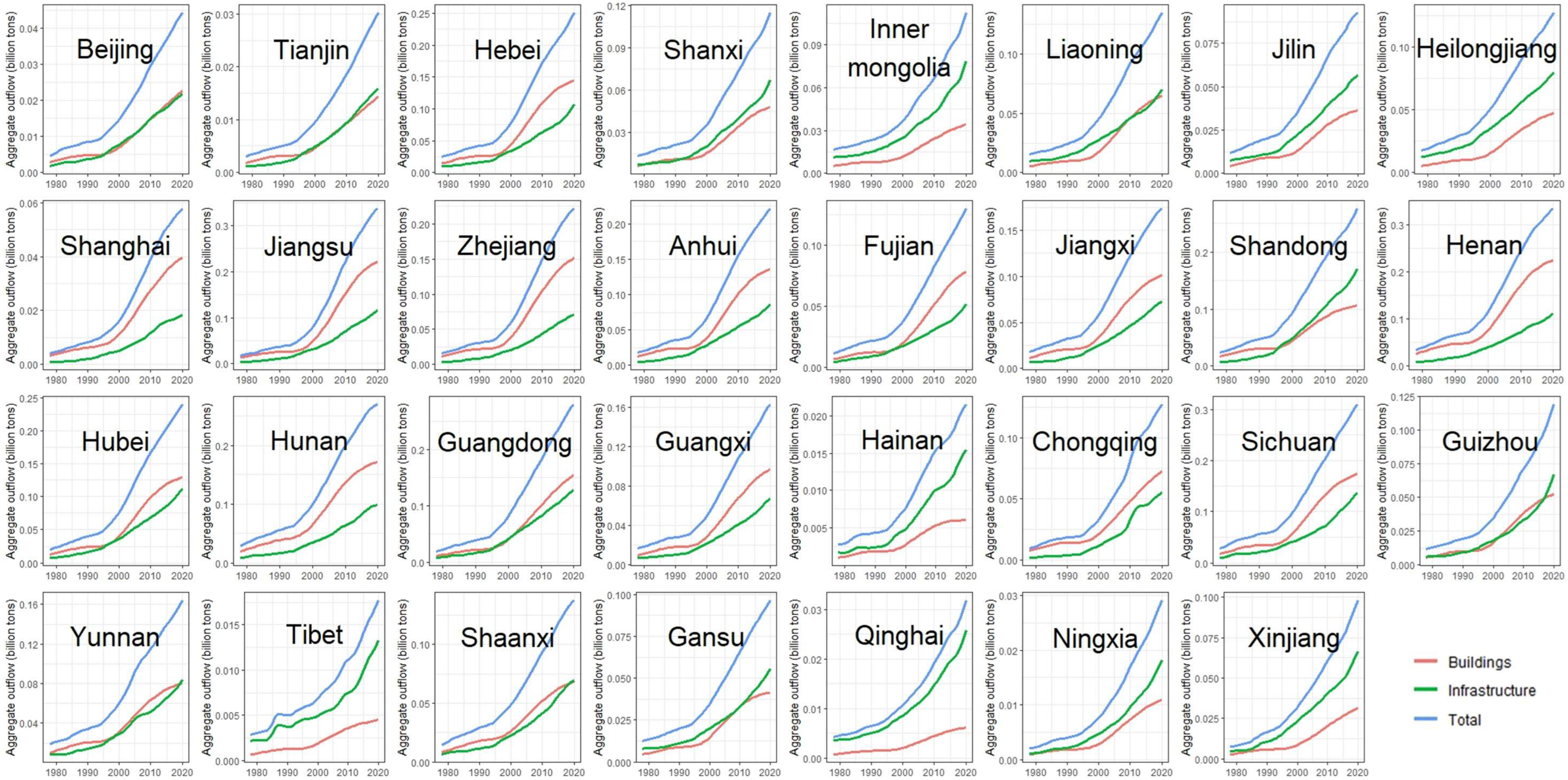

Figure S22 Aggregate outflow in provincial China (1978-2020). The outflows are classified by total, buildings, and infrastructure.

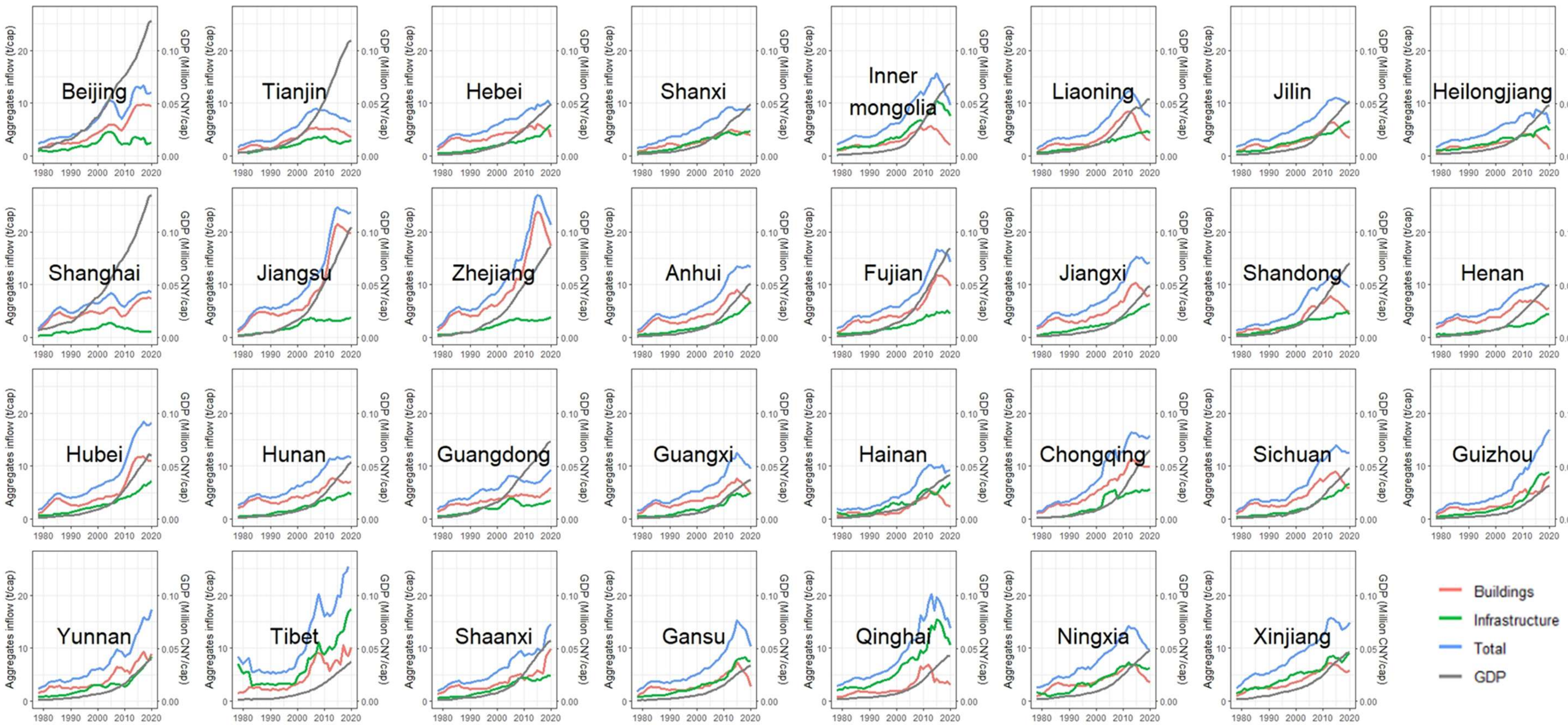

Figure S23 Provincial per capita aggregate demand and affluence (1978-2020). The demands are classified by total, buildings, and infrastructure. The data used are based on a five-year moving average.

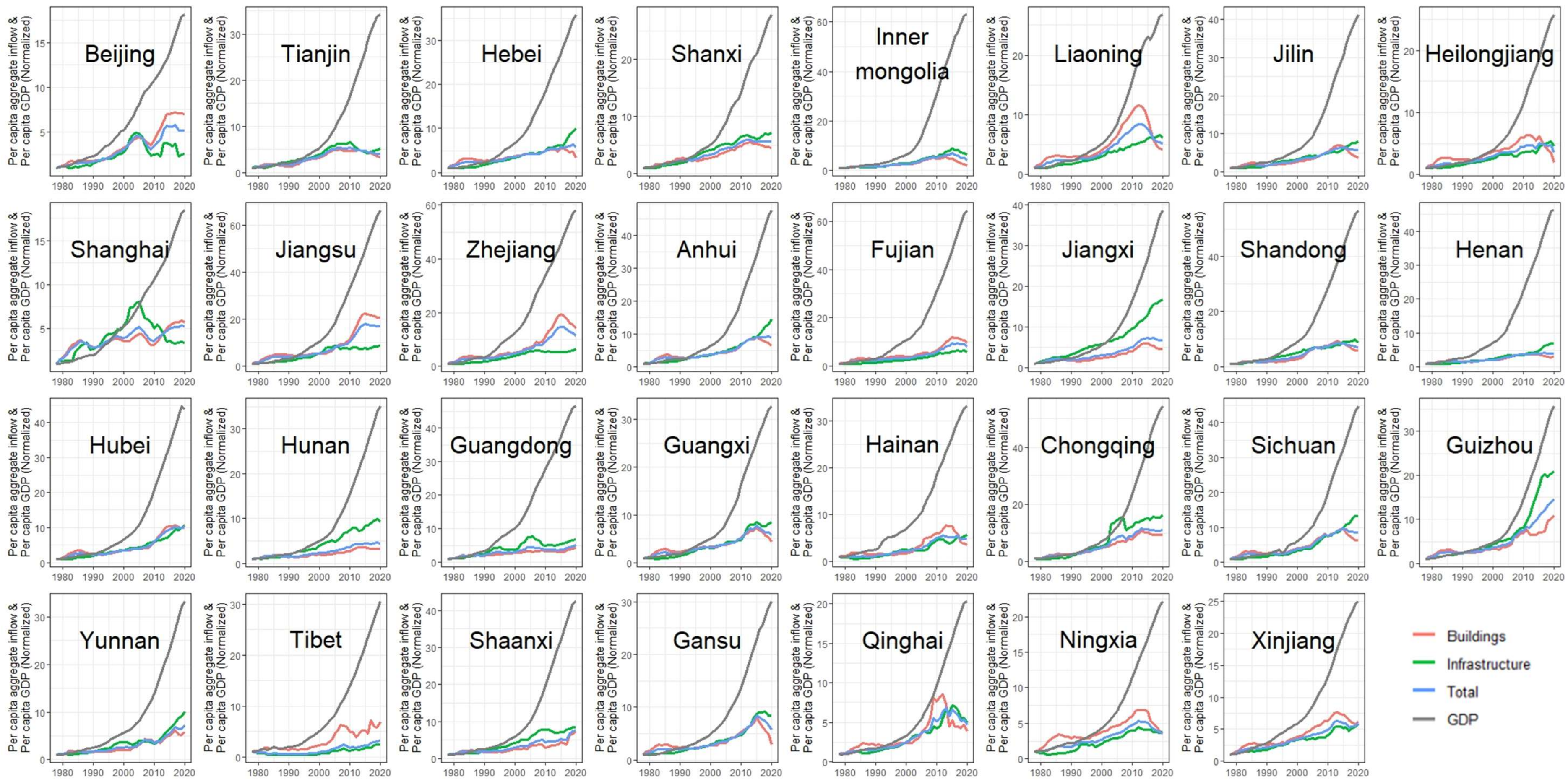

Figure S24 Provincial per capita aggregate demand, and per capita GDP (1978-2020). The demands are classified by total, buildings, and infrastructure. The data used are normalized.

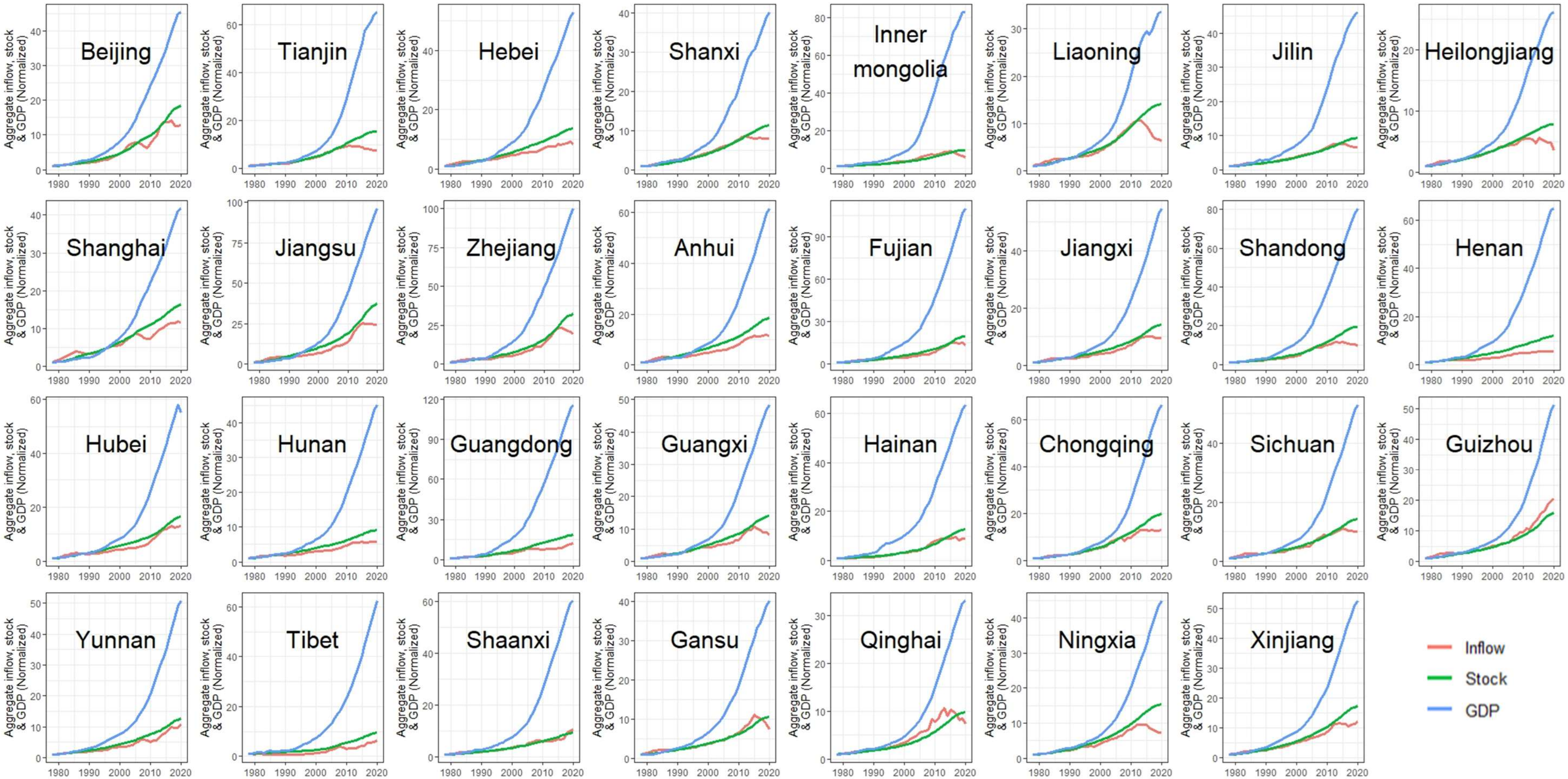

Figure S25 Provincial aggregate inflow, stock, and GDP (1978-2020). The data used are normalized.

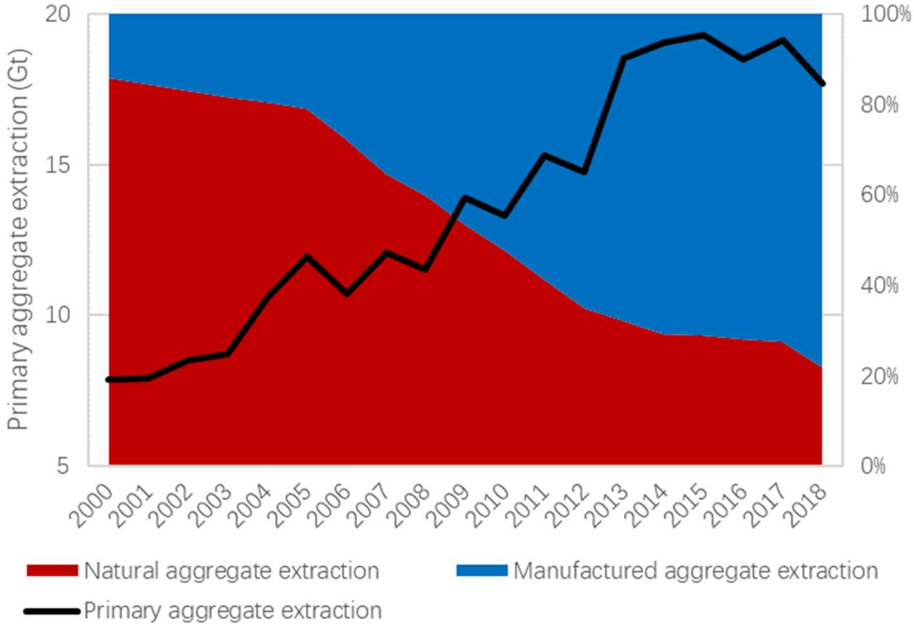

Figure S26 Primary aggregate extractions (natural aggregates vs. manufactured aggregates). The line graph illustrates the evolution of primary aggregate extraction, while the area graph depicts the changing proportions of natural aggregates and manufactured aggregates within that total.

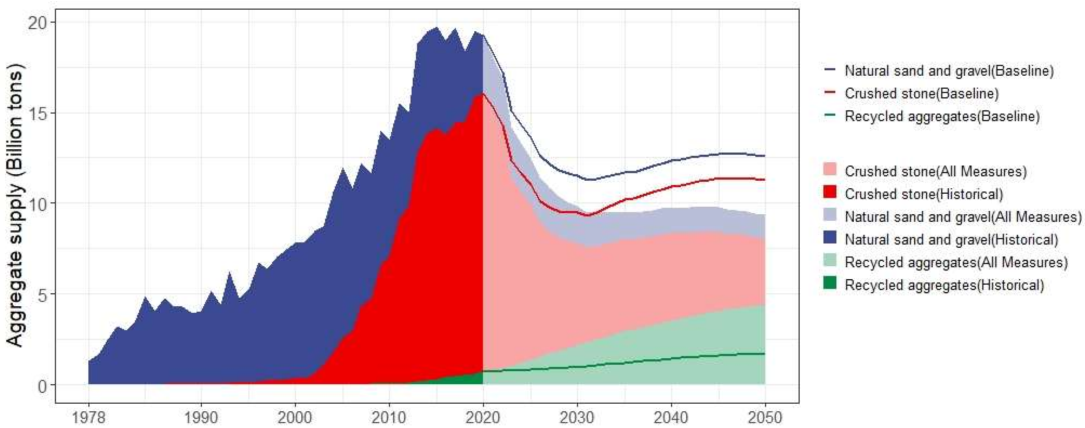

Figure S27 Evolution of China's aggregate supply. Historical evolution and future development of the supply of natural aggregates, crushed stone, and recycled aggregates under the Baseline and All Measures scenarios.

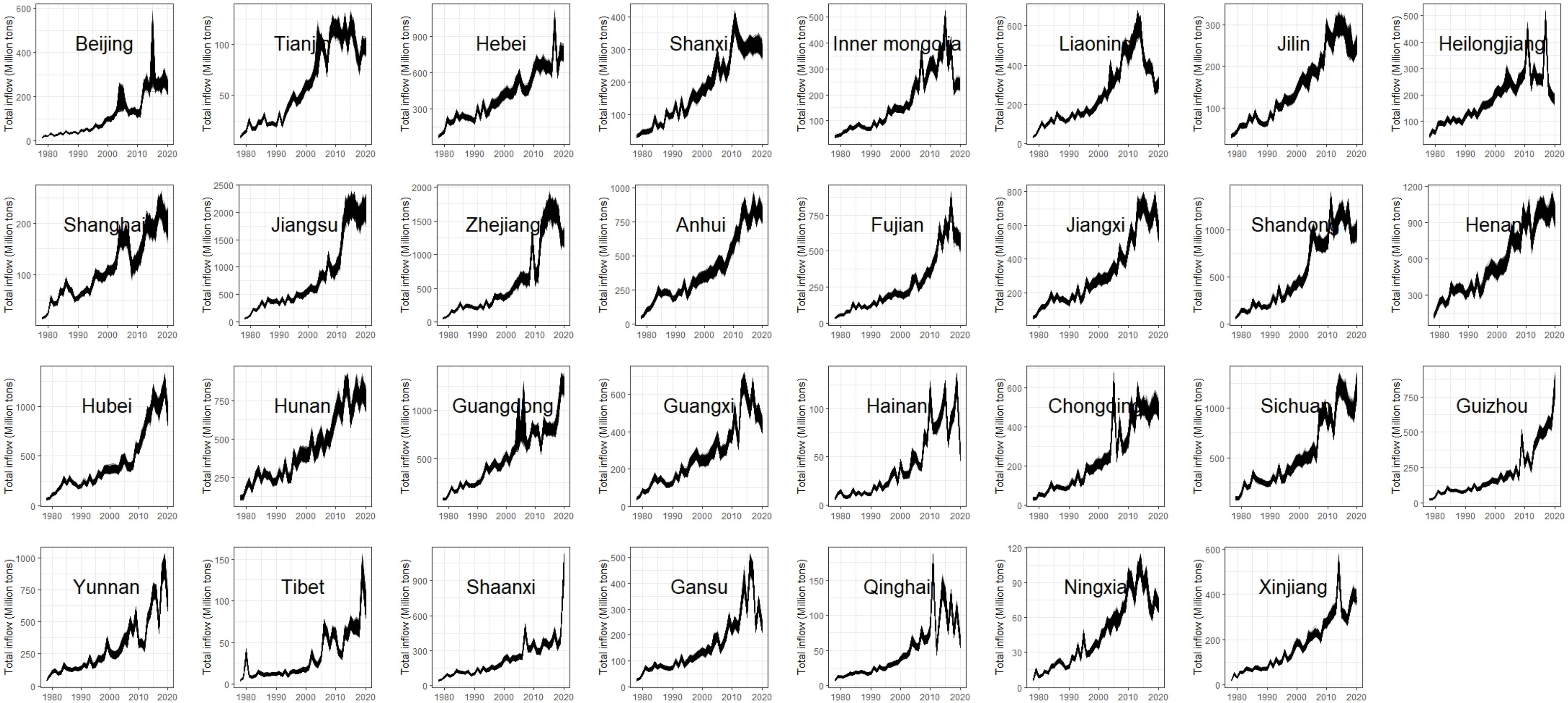

Figure S28 Uncertainty analysis of provincial aggregate inflow. The plot displays the results of each Monte Carlo simulation in the form of curve graphs, incorporating all outcomes from 10,000 simulation runs.

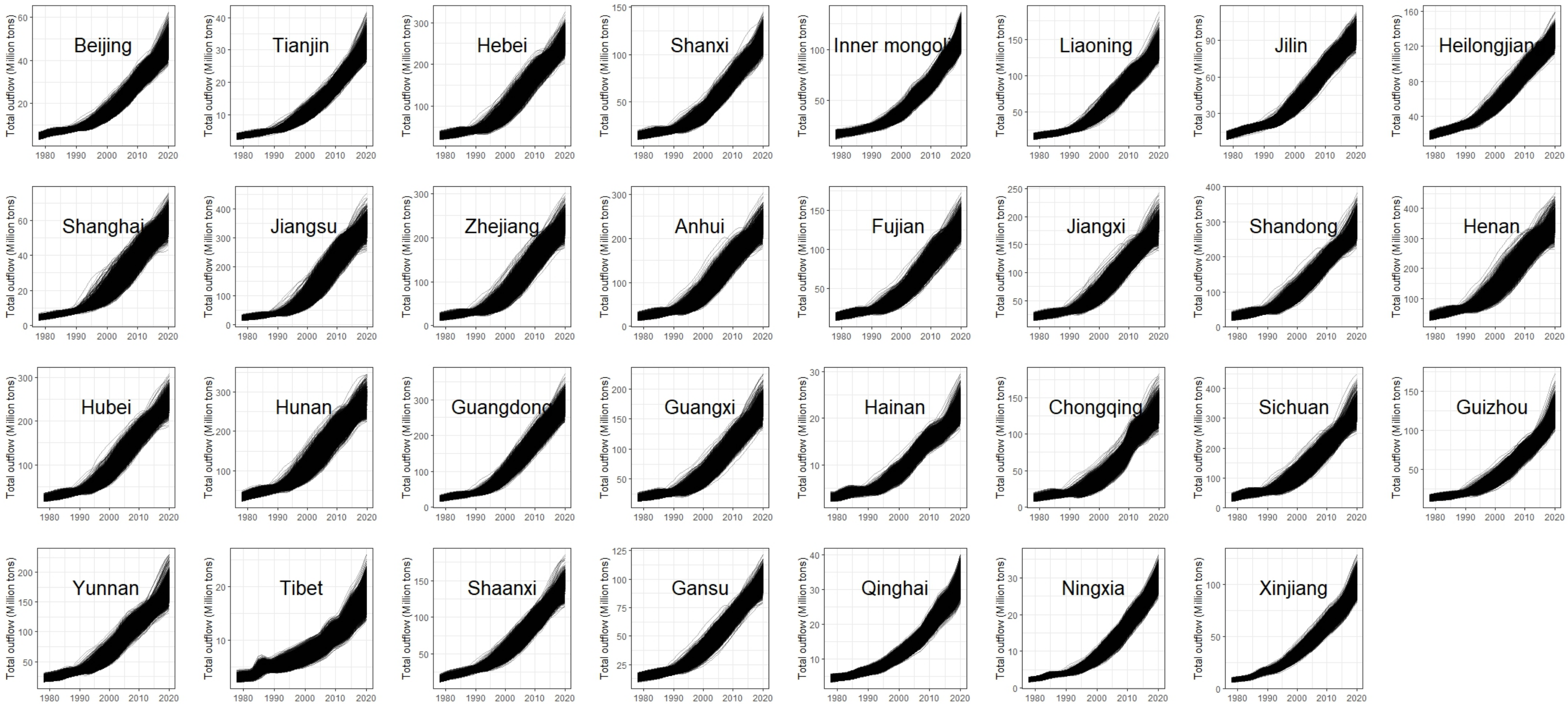

Figure S29 Uncertainty analysis of provincial aggregate outflow. The plot displays the results of each Monte Carlo simulation in the form of curve graphs, incorporating all outcomes from 10,000 simulation runs.

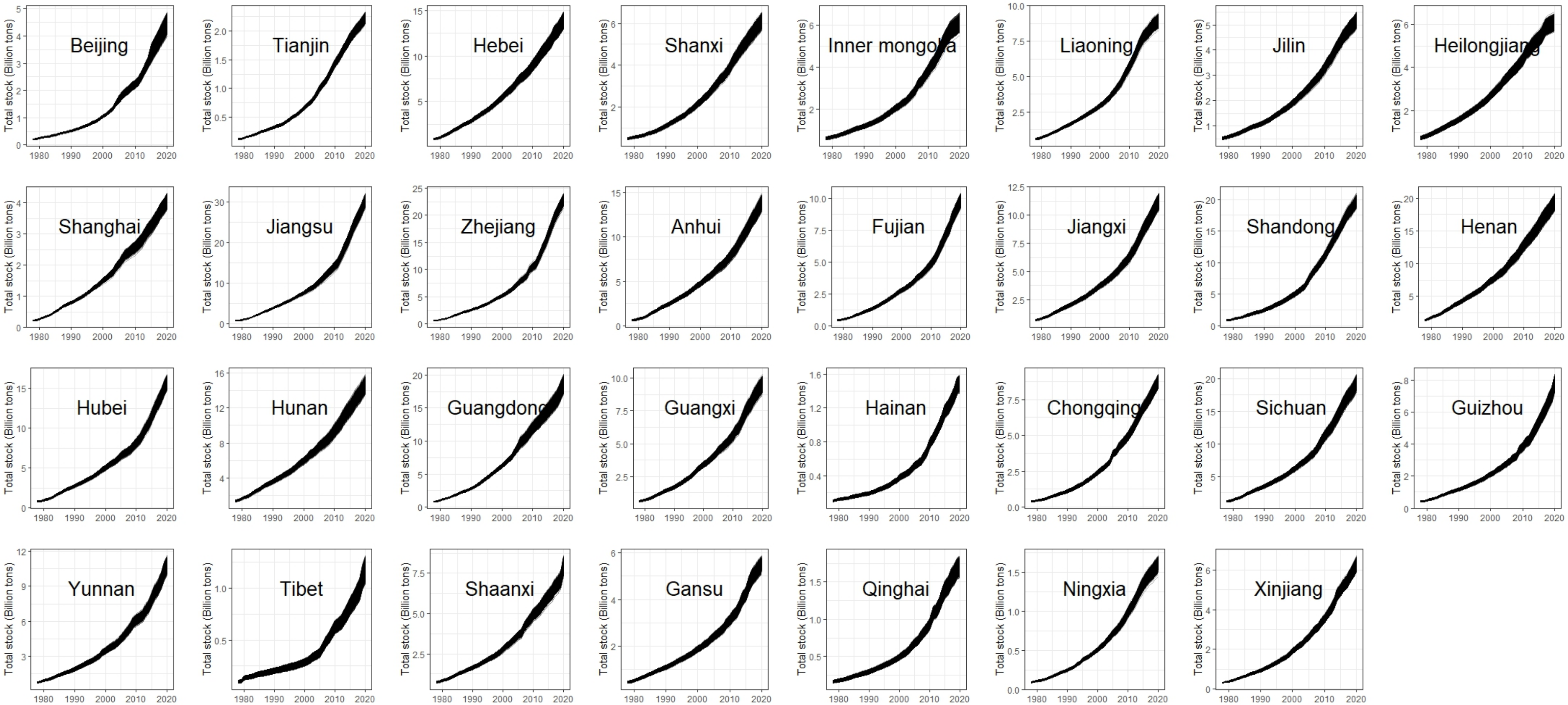

Figure S30 Uncertainty analysis of provincial aggregate stock. The plot displays the results of each Monte Carlo simulation in the form of curve graphs, incorporating all outcomes from 10,000 simulation runs.

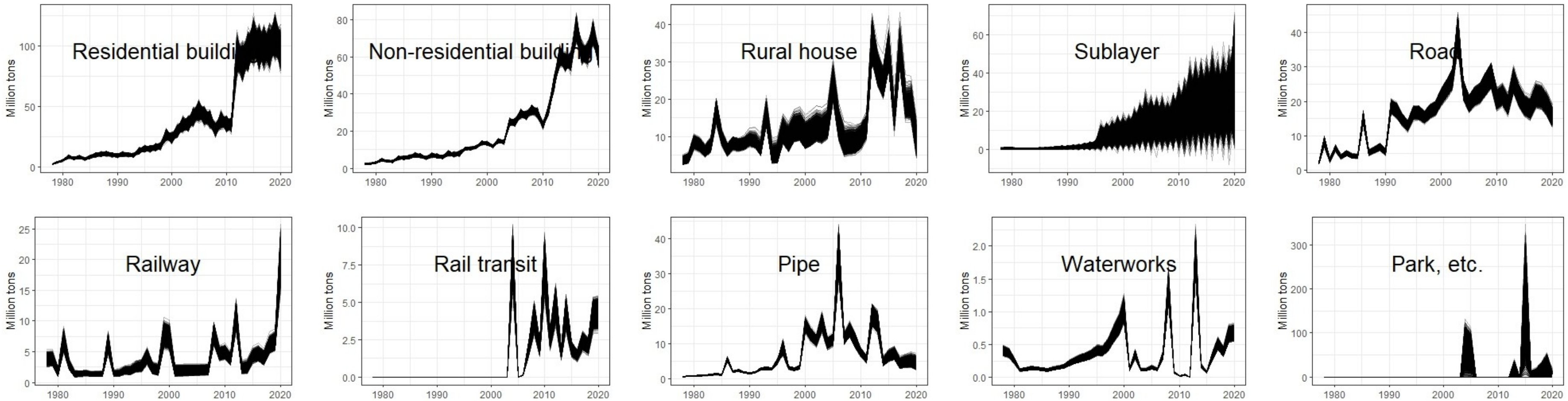

Figure S31 Uncertainty analysis of aggregate inflow by different final uses (take Beijing for example). The plot displays the results of each Monte Carlo simulation in the form of curve graphs, incorporating all outcomes from 10,000 simulation runs.

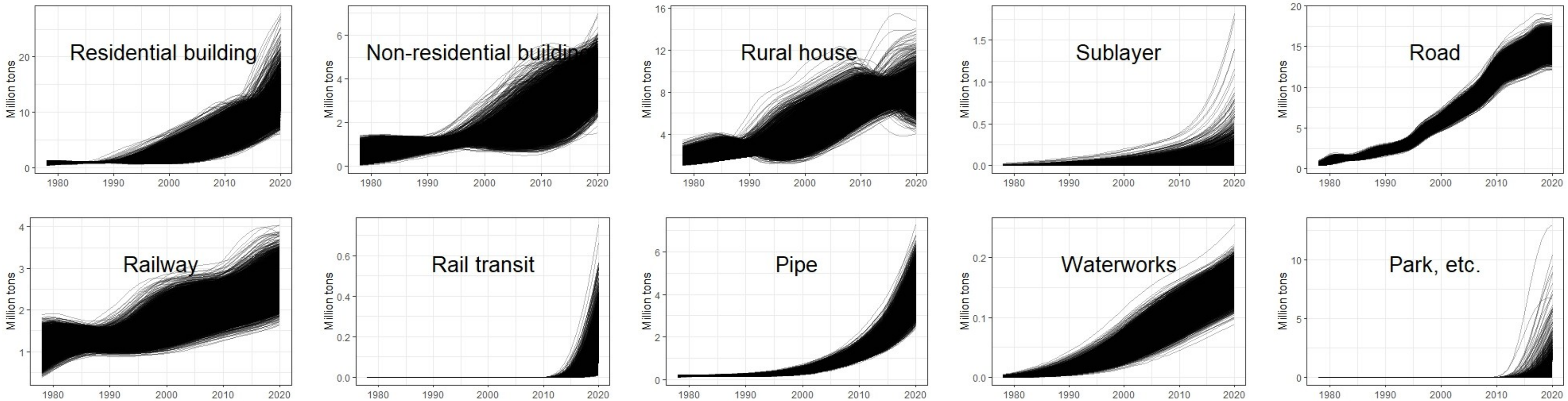

Figure S32 Uncertainty analysis of aggregate outflow by different final uses (take Beijing for example). The plot displays the results of each Monte Carlo simulation in the form of curve graphs, incorporating all outcomes from 10,000 simulation runs.

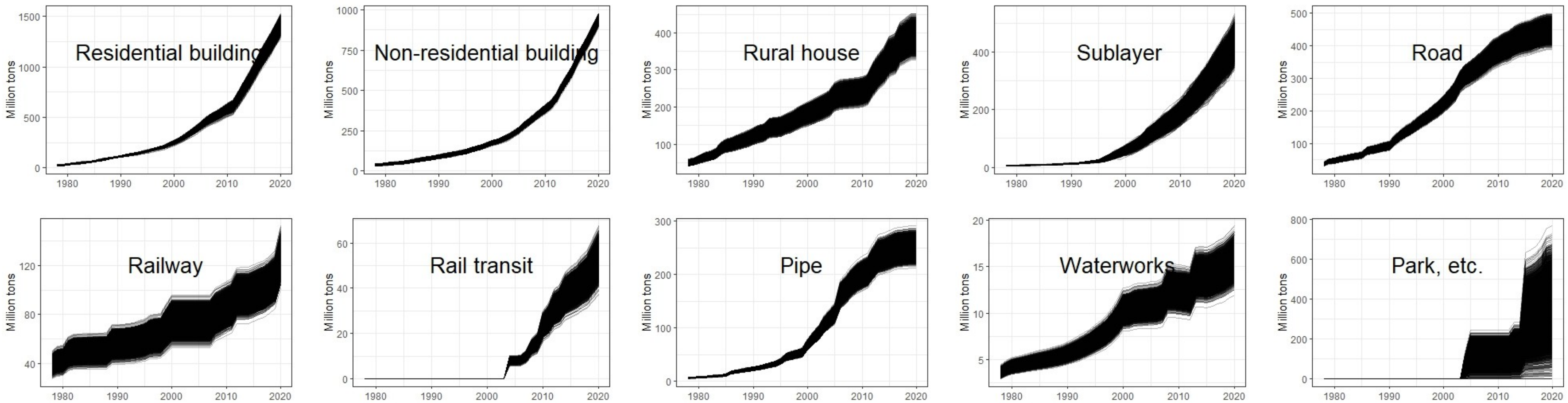

Figure S33 Uncertainty analysis of aggregate stock by different final uses (take Beijing for example). The plot displays the results of each Monte Carlo simulation in the form of curve graphs, incorporating all outcomes from 10,000 simulation runs.

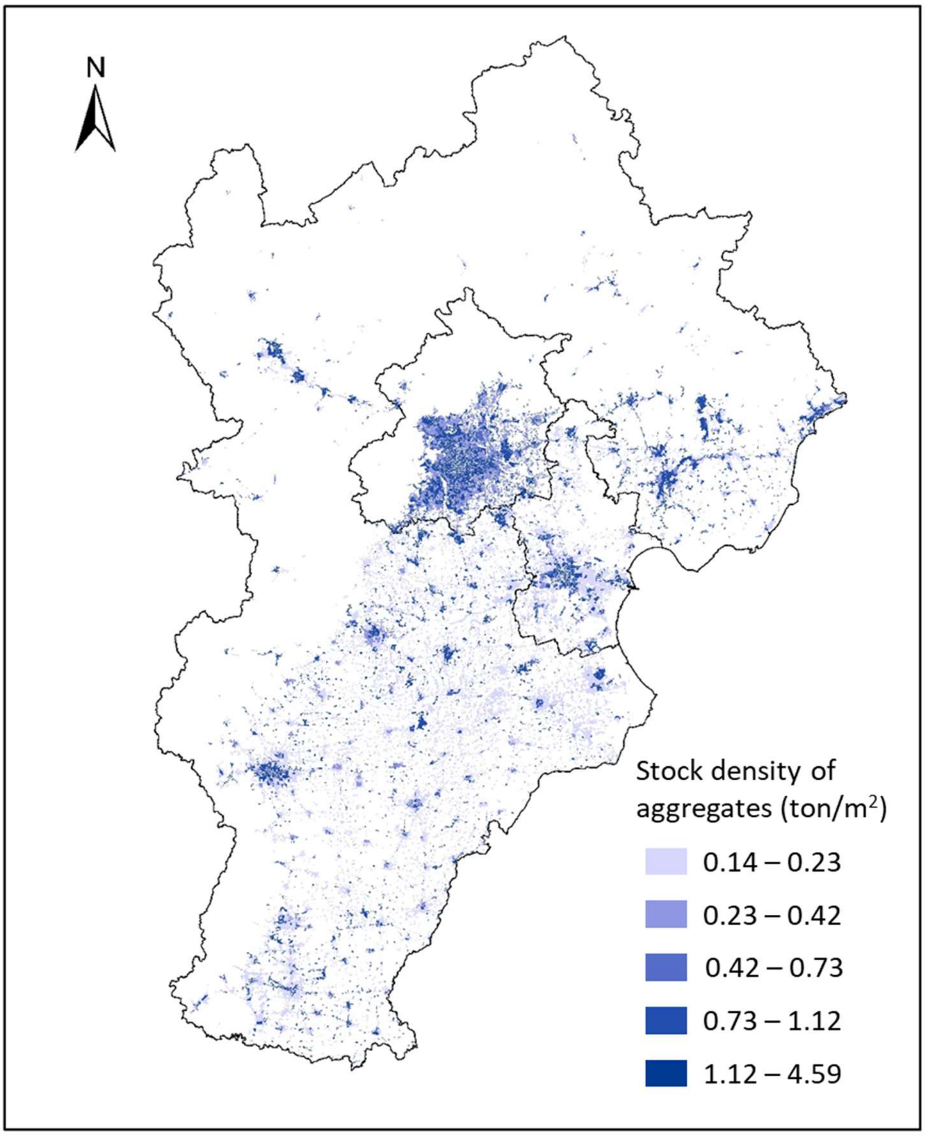

Figure S34 High-resolution Stock density of aggregates in the Jing-Jin-Ji area (2020, 1Km * 1Km). The map is based on the Essential Urban Land Use Categories (EULUC) map publicly released by Gong et al.[83], and the base map has not been altered.

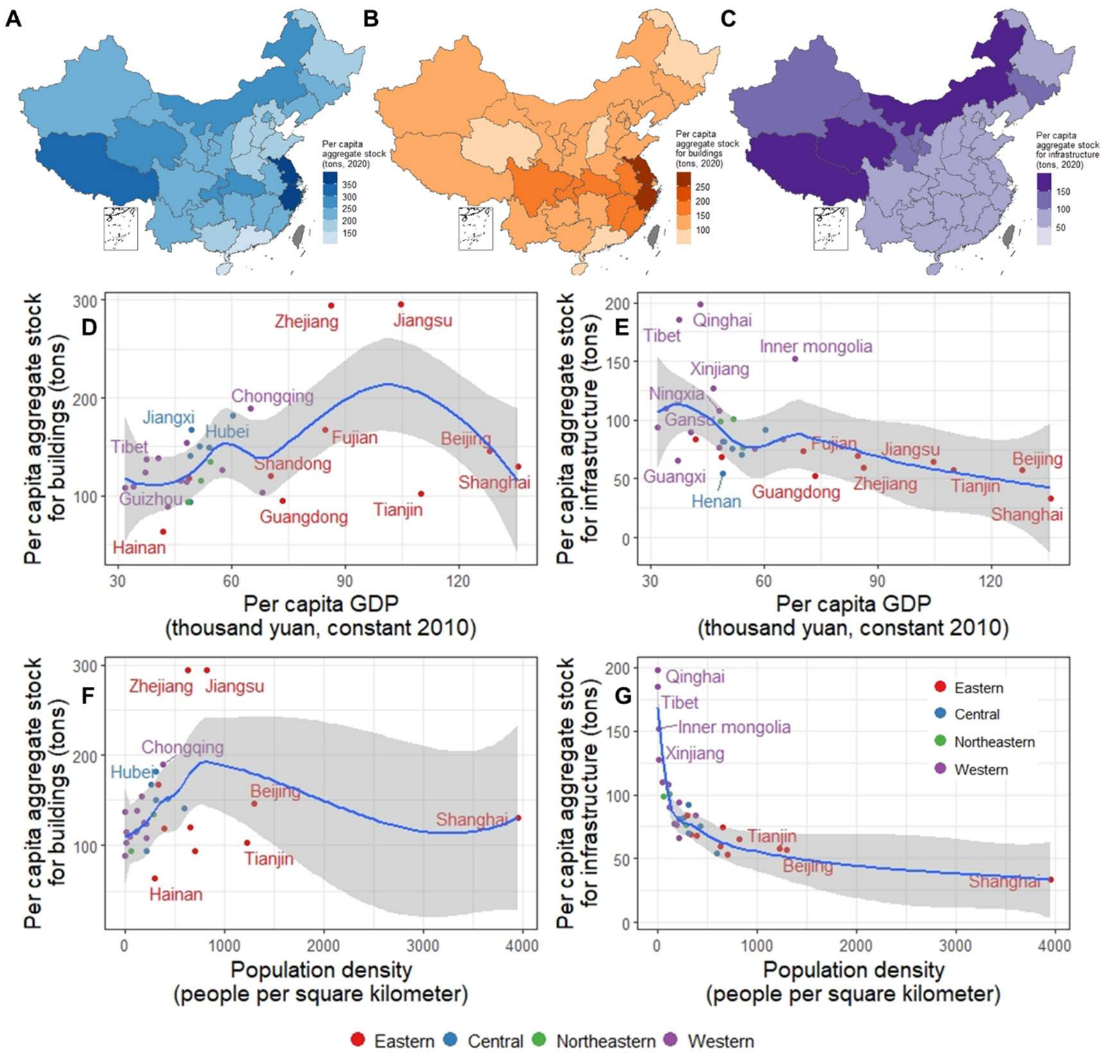

Figure S35 Patterns of Aggregate Stocks Per Capita Across Chinese Provinces (2020). (A)-(C) Distribution of per capita aggregate stocks in 31 provinces, segmented by all final uses, buildings, and infrastructure; (D)-(G) Correlations between population density and per capita GDP with respective aggregate stocks in buildings and infrastructure. The color-coding of data points and provincial labels corresponds to specific regions as detailed in Figure S2. The maps are produced based on the standard map (Approval No. GS(2024)0650) downloaded from the Standard Map Service website of the China National Administration of Surveying, Mapping and Geoinformation, with no modification to the base map.

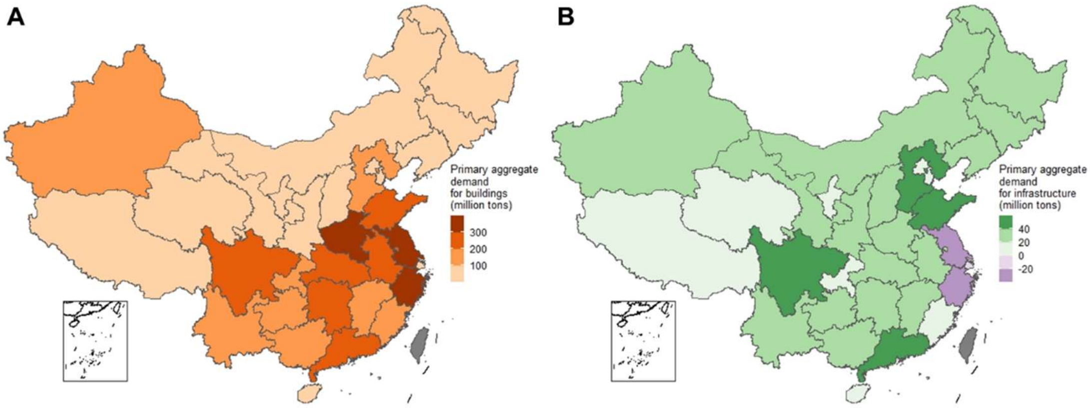

Figure S36 Primary aggregate demand for buildings and infrastructure in the 31 provinces in 2050. Primary aggregate demand is defined as the total aggregate demand minus recycled aggregate supply. The maps are produced based on the standard map (Approval No. GS(2024)0650) downloaded from the Standard Map Service website of the China National Administration of Surveying, Mapping and Geoinformation, with no modification to the base map.

Supplementary Tables

Table S1 Classification of Buildings and Infrastructure Categories

Category		Sub-category
Buildings	Building	Residential buildings (not including the rural house), Commercial buildings, Offices, Education & Culture & Healthcare & Research, Plant & Warehouses, Other buildings, Rural house
	Building sublayers	-
Infrastructure	Road	Expressway, Class Ⅰ, Class Ⅱ, Class Ⅲ, Class Ⅳ, Urban road, Rural road
	Rail	High-speed railway, General speed railway
	Pipeline	Tap pipe (in city, county, town, township, village), Sewer pipe (in city, county, town, township)
	Rail transit	Light rail, Subway
	Waterworks	-
	Parks etc.	-

Table S2 Indicators and data sources of building

Year	Indicator	Sources
1949-1995	Completed area of housing in society	National Bureau of Statistics - Annual data by province[18]
1996-2017	Completed area of buildings in the construction industry	China Statistical Yearbook on Construction[84]; EPS Dataset[19]
2018-2020	Completed area of housing in the construction industry	National Bureau of Statistics - Annual data by province[18]

Table S3 Future recycling rates of building demolished waste and construction waste under the improved recycling scenario

	Recycling rate			The ratio of the recycled parts used for buildings	The ratio of the recycled parts used for infrastructure	The ratio of the non-recycled part used for fillings	
	2021	**2030**	**2050**			**2021**	**2050**
Residential and non-residential buildings	8%	45%	50%	60%	40%	10%	60%
Rural houses	5%	18%	20%	60%	40%	0	30%
Building sublayers	80%	80%	80%	Only for foundation			
Construction wastes	5%	35%	40%	20%	80%	20%	80%

Table S4 Future recycling rate of various infrastructures under improved recycling scenario

	Recycling rate			The ratio of the non-recycled part used for fillings	
	2021	**2035**	**2050**	**2021**	**2050**
Highway, urban road, railway, rail transit, parks, etc.	40%	75%	80%	10%	50%
Rural road	10%	45%	50%	0	30%
Pipeline, waterworks	15%	45%	50%	0	60%

Table S5 Various terms and definitions of sand and gravel resources

Terms	Definition	Source
Sand	Sand is a granular mineral that does not stick together in a moist state (i.e., it is non-cohesive), where particles smaller than 4.75mm constitute no less than 50% of the mass fraction, and particles smaller than 75μm do not exceed 15% of the mass fraction.	ASTM D2487-00 ASTM D2488-00 EN ISO 14688-1:2018
Gravel	Gravel is a granular mineral that does not stick together in a moist state (i.e., it is non-cohesive), where particles larger than 4.75mm but smaller than 75mm constitute no less than 50% of the mass fraction, and particles smaller than 75μm do not exceed 15% of the mass fraction.	ASTM D2487-00 ASTM D2488-00 EN ISO 14688-1:2018
Rock	Rock is a firm solid structure with a certain tensile strength, formed by non-metallic minerals through long processes of sedimentation and other processes.	PIANC, 2017[85] Lu, N., Likos, W. J., 2006[86]
Aggregates	Aggregates are granular materials produced through natural extraction, processing, or recycling and regeneration. They are primarily used in the construction field, with particle sizes generally not exceeding 75mm.	ISO 19595:2017 EN 12620:2002 EN 13043:2002

Table S6 The definition of aggregates for construction in China's national standard [66]

Terms	Definition
natural sand	Under natural conditions, rocks are broken, weathered, sorted, migrated, and piled/sedimented, forming rock particles with a particle size of less than 4.75mm[66]. Note: Natural sand includes river sand, lake sand, mountain sand, and purified sea sand, but does not include soft, weathered particles.
manufactured sand	It is made from rocks, pebbles, mine waste rocks, and tailings as raw materials, and is processed by soil removal, mechanical crushing, shaping, screening, powder control, and other processes. The gradation, particle shape, and stone powder content meet the requirements and the particle size is less than 4.75mm particles[66]. Note: Manufactured sand does not include soft, weathered particles.
mixed sand	Aggregates made of manufactured sand and natural sand mixed in a certain proportion[66].
pebble	Under natural conditions, rocks are broken, weathered, sorted, migrated, piled/sedimented, and rock particles with a particle size greater than 4.75mm are formed[87].
crushed stone	Rock particles with a particle size greater than 4.75mm, are obtained by mechanical processing such as crushing and screening of natural rocks, pebbles, or mine waste rocks[87].

Table S7 The definition of recycled aggregates in China's national standard [67,68]

Terms	Definition
Recycled fine aggregate for concrete and mortar	It is processed from concrete, mortar, stone, bricks, etc. from construction waste, and is used to prepare particles of concrete and mortar with a particle size not larger than 4.75mm[67]
Recycled coarse aggregate of construction waste	Particles with a particle size greater than 4.75mm that are processed from concrete, mortar, stone, bricks, etc. from demolition, construction, decoration, and other production activities as well as existing construction waste[68]

Table S8 Sand and stone-related minerals included in the "China Land and Resources Statistical Yearbook"[61]

Category	Types
Industrial Sand and Gravel	Metallurgical Quartzite, Metallurgical Sandstone, Foundry Sandstone, Foundry Sand, Fertilizer Quartzite, Fertilizer Sandstone, Glass Sandstone, Cement Mixing Sandstone, Brick and Tile Sandstone, Ceramic Sandstone, Glass Sand, Cement Mixing Sand, Standard Cement Sand, Brick and Tile Sand
Construction Sand and Stone	Construction Dolomite, Construction Sandstone, Construction Sand, Construction Shale, Construction Olivine, Construction Pyroxenite, Construction Basalt, Construction Amphibolite, Construction Diorite, Construction Gabbro, Construction Andesite, Construction Dacite, Construction Nepheline Syenite, Construction Granite, Construction Rhyolite, Construction Tuff, Construction Marble

Table S9 Comparison of production of construction aggregates and industrial aggregates in various countries (2018, million tons)[64]

Country	Aggregates for construction	Industrial sand and gravel	Proportion of industrial sand and gravel to total aggregates
USA	2302	121	4.99%
France	429	9.31	2.12%
Germany	597	7.5	1.24%
Japan	424	2.52	0.59%
UK	276	4	1.43%
Others		17.2	
Total		335	

Table S10 Comparison between Manufactured Aggregates and Natural sand and gravel

	Manufactured Aggregates	Natural sand and gravel	
		River Sand	Sea Sand
Particle Shape	Irregular granularity, better cohesiveness, longer service life	Smooth particle shape, relatively poor adhesion	
Grading	Can be flexibly adjusted according to demand, capable of continuous grading	Single grading and not easily adjustable, stability varies with sand source batches.	
Fineness Modulus	Easily adjustable through the production process	Natural attribute decided, not easily adjustable	
Harmful Substances	Free of chloride ions and other harmful substances	Contains organic harmful substances	Contains chloride ions and shell-like organic substances
Raw Material Source	Wide range of raw materials, such as sandstone, limestone, granite, etc.	Limited to river sediments, dried riverbeds	Limited to the nearshore seabed
Resource Security	Abundant stone mine resources, ensuring the production of manufactured sand/stone	River and sea sand resources are increasingly depleted, with growing restrictions on extraction.	

Table S11 Data items and sources of the underlying data, material intensity, and average lifetime in Beijing as a case (Detailed data for all provinces see Supplementary Data 1)

Category	Sub-Category	Underlying data in 2020		Material intensity in 2020 (t/unit underlying data)	Average lifetime (year)	Model
Data sources of building		*Yearbooks*[84] *and Statistics*[18]		*Literature*[3,30,88]	*Literature*[31,89,90]	Inflow-driven model
Building	Residential building (not including the rural house)	Constructed floor area (kilo square meter)	59084	1645	25(1949–1978) 30(1979–2000) 35(2001–2020)	
	Commercial building		15515	1644	35(1949–1978) 40(1979–2000) 45(2001–2020)	
	Office		5145	1377		
	Education & Culture & Healthcare & Research		6723	1580		
	Plant & Warehouse		6106	1966		
	Other buildings		3309	1593		
Data sources of waterworks		*Yearbook*[22,35]		*Standard*[33,35] *and Report*[34]	*Standard*[33,35]	
Waterworks		Concrete consumption for waterworks (kilo cubic meter)	347	1960	50	
Data sources of road		*Yearbooks*[21,23,91,92] *and Statistics*[18]		*Literature*[30,56,88,93]	*Literature*[31,93] *and Standard*[24-26]	Stock-driven model
Road	Express highway	Road length (km)	1173	54600	10	
	Class Ⅰ		1369	26880	10	
	Class Ⅱ		3996	8400	8	
	Class Ⅲ-Ⅳ		15726	4500	6	
	Town road		11208	8200	8	
	Rural road		18241	5729	6	

Data sources of railway		*Yearbook*[92] *and Statistics*[18]		*Literature*[30,31,34,90,93]	*Standard*[27] *and Literature*[31,90]	
Railway	High-speed railway	Railway length (km)	431	120000	30	
	General speed railway		1670	43000	30	
Data sources of rail transit		*Yearbook*[23]		*Literature*[30,31,90]	*Literature*[93]	
Rail transit	Light rail	Rail transit length (km)	-	-	-	
	Subway		754	70000	30	
Data sources of pipeline		*Yearbooks*[21,23] *and Statistics*		*Literature*[31,90,93]	*Literature*[31,90,93]	
Pipeline	Tap pipe	Pipeline length (km)	42452	3300	30	
	Sewer pipe		19344	3300	30	
Data sources of rural house		*Statistics*[18]		*Literature*[31,90]	*Literature*[31,89,90,93]	
Rural house		Rural house area = Rural population * Per capita floor area (kilo square meter)	287746	1253	30	

Table S12 Overview of material intensity adopted in this study across province and year (see the detailed data in the supporting data file)

Final use	Material	Underlying data		Unit	Material intensity		Unit	Model
		Maximum	Minimum		Maximum	Minimum		
residential building	Fine aggregates	570.3	1.56	million m2	1005.2	789.7	kg/m2	inflow-driven
residential building	Coarse aggregates	570.3	1.56	million m2	924.7	689.9	kg/m2	inflow-driven
commercial building	Fine aggregates	25.4	0.08	million m2	732.1	605.6	kg/m2	inflow-driven
commercial building	Coarse aggregates	25.4	0.08	million m2	1032.0	795.8	kg/m2	inflow-driven
office	Fine aggregates	30.1	0.09	million m2	669.9	554.2	kg/m2	inflow-driven
office	Coarse aggregates	30.1	0.09	million m2	808.3	623.4	kg/m2	inflow-driven
hospital/school/research building	Fine aggregates	29.4	0.11	million m2	706.5	584.5	kg/m2	inflow-driven
hospital/school/research building	Coarse aggregates	29.4	0.11	million m2	988.8	762.5	kg/m2	inflow-driven
plant	Fine aggregates	111.1	0.05	million m2	1008.6	843.7	kg/m2	inflow-driven
plant	Coarse aggregates	111.1	0.05	million m2	1338.5	992.9	kg/m2	inflow-driven
other buildings	Fine aggregates	11.8	0.17	million m2	759.1	628.0	kg/m2	inflow-driven
other buildings	Coarse aggregates	11.8	0.17	million m2	950.5	733.0	kg/m2	inflow-driven
rural house	Fine aggregates	3847.4	133.6	million m2	626.7	626.7	kg/m2	stock-driven
rural house	Coarse aggregates	3847.4	133.6	million m2	658.4	658.4	kg/m2	stock-driven
express highway surface layer	Aggregates	10488.0	106.0	km	18200.0	18200.0	t/km	stock-driven
1st-class highway surface layer	Aggregates	15819.0	470.0	km	8960.0	8960.0	t/km	stock-driven
2nd-class highway surface layer	Aggregates	28602.0	1060.0	km	2800.0	2800.0	t/km	stock-driven
highway below 2nd-class surface layer	Aggregates	364934.0	7810.0	km	1125.0	1125.0	t/km	stock-driven
express highway sublayer	Aggregates	10488.0	106.0	km	36400.0	36400.0	t/km	stock-driven
1st-class highway sublayer	Aggregates	15819.0	470.0	km	17920.0	17920.0	t/km	stock-driven
2nd-class highway sublayer	Aggregates	28602.0	1060.0	km	5600.0	5600.0	t/km	stock-driven
highway below 2nd-class sublayer	Aggregates	364934.0	7810.0	km	3375.0	3375.0	t/km	stock-driven
city road surface layer	Aggregates	50860.8	988.3	km	2800.0	2800.0	t/km	stock-driven
city road sublayer	Aggregates	50860.8	988.3	km	5600.0	5600.0	t/km	stock-driven
county road surface layer	Aggregates	12633.7	462.0	km	1694.3	1694.3	t/km	stock-driven

county road sublayer	Aggregates	12633.7	462.0	km	5082.8	5082.8	t/km	stock-driven
town road surface layer	Aggregates	49415.6	2048.3	km	1694.3	1694.3	t/km	stock-driven
town road sublayer	Aggregates	49415.6	2048.3	km	5082.8	5082.8	t/km	stock-driven
rural road surface layer	Aggregates	340607.9	11139.8	km	1432.3	1432.3	t/km	stock-driven
rural road sublayer	Aggregates	340607.9	11139.8	km	4296.8	4296.8	t/km	stock-driven
general-speed railway	Aggregates	16874.6	583.9	km	43000.0	43000.0	t/km	stock-driven
high-speed railway	Aggregates	3566.2	208.0	km	120000.0	120000.0	t/km	stock-driven
rail transit	Aggregates	940.8	24.0	km	70000.0	70000.0	t/km	stock-driven
city tap pipe	Aggregates	128119.0	1771.4	km	3300.0	3300.0	t/km	stock-driven
city sewer pipe	Aggregates	122541.5	861.2	km	3300.0	3300.0	t/km	stock-driven
county tap pipe	Aggregates	22385.4	1595.9	km	3300.0	3300.0	t/km	stock-driven
county sewer pipe	Aggregates	18647.1	1091.3	km	3300.0	3300.0	t/km	stock-driven
town tap pipe	Aggregates	63772.5	2630.9	km	3300.0	3300.0	t/km	stock-driven
town sewer pipe	Aggregates	21776.5	611.0	km	3300.0	3300.0	t/km	stock-driven
rural tap pipe	Aggregates	168383.3	9644.8	km	3300.0	3300.0	t/km	stock-driven
park. etc.	Aggregates	847.0	9.00	million m2	1.00	1.00	t/square meter	stock-driven
waterworks	Fine aggregates	12.6	0.35	million m3	0.70	0.70	t/cubic meter	stock-driven
waterworks	Coarse aggregates	12.6	0.35	million m3	1.26	1.26	t/cubic meter	stock-driven

Table S13 Key Issues and Investigative Regions in Aggregate Resource Management

Opinions	Regions for investigation	Sources
Over extraction of aggregate resources brought about a scarcity of resources, with the demand exceeding supply, and prices soaring.	Global, Southeast Asia, etc.	[38,94-99]
The extraction of aggregate resources has a significant impact on the local environment and ecology, such as biodiversity losses, Land losses, hydrological function change, water pollution, infrastructure damage, climate change, landscape change, extreme events, and so on.	China, Southeast Asia, India, Iran, etc.	[38,94,95,99-103]
Gaps in the current governance system for aggregate resources and a series of cascading impacts caused by illegal extraction.	Southeast Asia, India, etc.	[38,94,95,99,104,105]
The environmental and social problems caused by the cross-border trade of aggregates intensify the inequity of regional development	Southeast Asia, Dubai, etc.	[38,94,95,99,106]
New sources of aggregates to alleviate the global sand crisis	Greenland	[107,108]
Comparison of natural aggregates and manufactured aggregates for sustainability	India, Malaysia, etc.	[109,110]
Life cycle assessment of aggregates from recycled materials and virgin sources	Hong Kong	[111-114]

Table S14 Summary of quantitative analysis of material resources

Model	Material resource	Time Range	Region	Source
Economy-wide material flow analysis (EW-MFA)	All-set material resources	1878-2005	Japan	[115]
Dynamic material flow analysis (d-MFA)	Metal mineral	Review study		[12]
Material Input Stock and Output model (MISO)	All-set material resources	1900-2010 & 2011-2050	Global	[1]
Time-Cohort-Type (TCT) method	Cement	1931-2014	Global	[116]
Global dynamic building-sand model (GloBus)	Sand used in concrete and glass in residential and commercial buildings	2020-2060	Global	[39]

Table S15 Uncertainty Settings of Parameters for Various Final Uses in Monte Carlo Uncertainty Analysis[1]

	Stock/inflow model input uncertainty (±)	Lifetime expectation uncertainty (±)
Road	15%	15%
Railway	15%	15%
Rail transit	15%	15%
Pipeline	15%	15%
Waterworks	15%	15%
Building	15%	30%
Rural house	15%	30%
Sublayer	60%	30%
Park, etc	60%	30%

Table S16 Maximum Deviations of Aggregate Stock, Inflow, and Outflow in Each Province from Monte Carlo Analysis

	inflow	stock	outflow
Beijing	30.9%	13.9%	49.3%
Tianjin	22.8%	13.3%	49.4%
Hebei	24.9%	15.1%	49.6%
Shanxi	22.2%	15.8%	49.7%
Inner Mongolia	20.9%	16.0%	49.5%

Liaoning	25.2%	13.2%	49.2%
Jilin	20.0%	14.6%	49.4%
Heilongjiang	21.3%	14.7%	49.6%
Shanghai	19.6%	13.2%	49.6%
Jiangsu	27.9%	15.2%	49.5%
Zhejiang	28.4%	15.9%	49.7%
Anhui	29.7%	16.4%	49.8%
Fujian	27.9%	16.4%	49.7%
Jiangxi	28.4%	14.9%	49.6%
Shandong	29.7%	15.9%	49.7%
Henan	26.8%	16.1%	49.7%
Hubei	27.6%	15.6%	49.6%
Hunan	24.2%	15.9%	49.7%
Guangdong	25.8%	14.6%	49.4%
Guangxi	27.1%	15.4%	49.7%
Hainan	24.5%	14.0%	49.5%
Chongqing	30.7%	16.9%	49.9%
Sichuan	28.3%	15.0%	49.6%
Guizhou	28.3%	15.4%	49.8%
Yunnan	26.7%	15.8%	49.5%
Xizang	25.3%	15.7%	49.6%
Shaanxi	23.7%	15.4%	49.5%
Gansu	26.4%	14.4%	49.5%
Qinghai	28.9%	16.2%	49.8%
Ningxia	24.4%	13.8%	49.7%
Xinjiang	26.9%	13.7%	49.7%

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