nature portfolio

Peer Review File

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

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Parts of this Peer Review File have been redacted as indicated to remove third-party material.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Sand is the second most exploited natural resource in the world after water. Sand sustainability has become an important topic in recent years. As the demand for sand resources is increasing, meeting the demand and reducing its negative impacts are critical. This paper takes China as an example and examines the potential of recycling in sand sustainability. The authors have found that recycling can play a very important role in the future supply of sand. The results can have great implications for construction and infrastructure development. The results of this paper are trustworthy, and the methods are innovative. It is the first to explore the potential of recycling in balancing the sand supply and demand. The methods provided in the paper are reproducible. Following are several suggestions to improve the paper:
1) The authors provide much information; they cover the transition from natural aggregate to manufactured aggregates, recycling aggregates, provincial disparity, and sand supply vs. sand demand. However, the main story is not clear enough.
2. Sand and gravel supply is not only determined by the resource itself, recycling rate, but, most importantly, by policies, resource governance, market, and illegal mining (See Lamb 2023, EXIS. There are some more deep insights). The supply-side analysis in this research is not well established; for example, the provincial government issues the maximum available mining volume for the main rivers annually in Guangdong Province of China. However, the cities have their mining plan for the small rivers. Besides, does the supply-side model include illegal sand mining? If not, how does this affect the results?
3. “China has shifted from natural to manufactured aggregates to meet high demand.” do the authors have any data to clarify this transition?
4. Diving deeper into the results, trends, and numbers the authors have mentioned is significant. Interesting results with explanations can help the readers understand the main findings better. For example, what’s behind the “aggregate demand in 25 of the 31 provinces peaked before 2020, excluding some less-254 developed western regions and Guangdong” (Line 254-255).
What drives the growth rate of stocks in most provinces is projected to be greater than 2% (Line 280-281, as well as this paragraph).
What’s behind “for buildings, the proportion of waste recycled and used for fillings is projected to increase from 12% to 66%” (Line 195-196); why, how, and what does it mean?
5. “Recycling of aggregate waste in China is expected to rise from 734 million tons (Mt) in 2021 to 4.5 billion tons (Gt) by 2050 under the All Measures scenario, increasing its share from 13% to 46% of total waste (Figure 2D).” Recycling aggregates have a market in China, and to make sure recycling aggregates are being used, technology is required to produce high-quality products at cheaper prices and people's acceptance. Except for these, have the authors considered that some concrete products have their maximum recycling aggregate ratio? Because too much aggregate recycling can affect the quality of the concrete.
6. Has the research considered the trade between provinces? It can affect the material supply. How does the model deal with this? Have the authors considered international trade? How is that calculated in the model? As we know, Hong Kong imports a lot of sand from mainland China.
7. The authors should consider using the word ‘crisis’ more carefully. “We emphasize that the sand crisis is not a global issue, but a local one, making regional and local studies crucial.” (Line 374-375) As Lamb said, “Scarcity is political: who defines scarcity? How does this shape who is involved and what solutions are possible?” (Lamb, 2023) Is the crisis a short-

term problem or long-term? What does the local sand crisis mean?
8. For audiences from other countries, what does the Chinese story tell us? What are the differences between China and other countries?
9. what is the story regarding the difference between the provinces inside China?
10.The authors also need to consider the feasibility of recycling sand. Currently, sand construction waste is always used in landfills, as the cost of recycling sand from construction waste is expensive compared to others. The authors can also include the cost-benefit of the recycling approach.

(Remarks on code availability)
The paper can be reproducible as the authors have provided code for CHAMPS, and the code is executable.

Reviewer #2

(Remarks to the Author)
General

This article evaluates the aggregate consumption in China between 1978 and 2050, with a prospective scenario-based modeling after 2020. While aggregates are an important resource as showed in the "main' section of the manuscript, we found hard to follow the logic of the "main section", to be convinced by the conclusions of the article, by the scenarios, and we found the method extremely hard to understand, both in the manuscript and the supplementary materials. I am still unsure of what have been done, as some variables seem not to be explained from the equations of the SM. The objective of the study are not clearly stated to my opinion. A lot of energy has been spent to define the different types of aggregates (especially in SM), but the terms used in the manuscript are not always the best choice to be understandable to my point of view (e.g., "manufactured aggregates"). Moreover, the title states that the study is about sand, while the article deals with all aggregates (including gravel, and crushed stone). The data used are a mix of literature-derived and expert insights, that would deserve being better referenced in some parts of the method, and it makes it hard to assess their quality. We found that the scenarios are also not extremely well supported (justification of the scenarios choice?), and one could argue that it is hard to assess the robustness of the results without at least sensitivity analyses on key parameters, such as lifetimes of products or recycling rates. There are some figures of uncertainty analyses (a lot of them) in the SM, but no explanation of what they are, and how they were generated. In the end, the results fall a bit short, with bland recommendations such as promoting circular economy to reduce consumption of sensitive virgin resources.

To be more specific on the "main" section of the article, the writing and argumentation about the importance of the research and its findings is a bit clumsy, with some approximations and common places, and little gaps in the logical flow of the text. We wish more rigor about facts and a clearer argumentation. The structure could be enhanced (for instance: avoiding talking about sand crisis, then local aggregate shortages, and final sand crisis again (p3)). The "main" part of the manuscript relies on an eclectic body of literature, while we would like to know more about similar attempts of quantification, methodologically speaking, and know more what other models did (see suggestions below).

The manuscript (and SM) also lacks some references along the text. Example: "Using one cubic meter of concrete in China typically requires 1.8 tons of aggregates (l53-54), and other following figures: are they from the SN?

Below are some specific suggestions, but we recommend the authors to work in depth on their study and manuscript, beyond these suggestions.

Manuscript

Abstract:
• the method is not specified: "a scenario-based model that tracks flows and stocks" is quite unspecific
• the concept of stock saturation may not be clear for readers

l32 : change for hyphen for dash

l37-38: "stabilizing at around half of 2020 levels under circular scenarios, with provincial per capita stocks approaching saturation around 2040": rephrase, unclear

l38-39: "We find a major shift from natural to manufactured aggregates": if it is "under circular scenarios" as written in the previous sentence, the contrary would have been quite surprising!

L49 "(stone can be used once crushed)": this addition cuts the flow of reading and may be unnecessary to the demonstration.

L50: "Gt (billion tons)": full form and abbreviation in brackets is most common

L60-61: "Often extracted from rivers, lakes, and mountains, sand and gravel are vital for construction but are often overexploited in certain regions, leading to a sand crisis": I am not sure to understand why we talk about sand and gravel's overexploitation, to finally talk about a sand crisis only (and not gravel, if it is also overexploited. And why starting with "Often extracted from rivers, lakes, and mountains": does it help the argument? I personally wonder the link between where it is often extracted from, the sand crisis, and why we only talk about these three sources of aggregates when I read the sentence.

L60: “sand and gravel are vital for construction”: in modern construction techniques yes, but construction is possible without sand and gravel I believe, with other natural materials (straw, wood, clay, etc.), so it may not be “vital”. Rephrase.

L63: are we talking about “natural replenishment” on a biocentric aspect, or “aggregate supply”, on a more technocentric aspect? I would have assumed that the natural replenishment of aggregates has been surpassed by aggregate demand as soon as concrete and asphalt concrete construction has been developed.

L64-65: “particularly from waterbody extraction”: I believe there is a confusion between stock and flow: the stocks are being depleted everywhere because the creation flows are so slow. The stock is been depleted faster in waterbodies because it costs less to extract than from hard rocks.

L65-67: “More sustainable alternatives, such as manufactured aggregates from rock quarrying and recycled aggregates from construction and demolition waste (CDW), offer solutions but require significant industrial inputs and careful ecological management.”: there are no references here, and first thing this sentence questions is: what is “more sustainable”? From which point of view? Which indicators? We can probably show that aggregates from waterbody are more sustainable on some indicators based on LCA: for instance, it consumes less energy to be produced, deteriorates machinery less, so globally the carbon footprint per ton is often smaller than those from hard rocks (see your ref #16).

L65: “manufactured aggregates from rock quarrying”: are you talking about natural aggregates produced from crushed rocks from quarries, or by-products of other manufacturing industries? Unclear. Please specify in the different places where you use manufactured aggregates, as I am not sure it is a dedicated term (e.g., l337). Crushed stones/ aggregates is probably a clearer term.

L68-69: “Life Cycle Assessment (LCA) has identified distinct environmental impacts of both traditional and alternative aggregates”: I do not understand this sentence. LCA proposes to quantify specific environmental impacts, this impact being somewhere between 0 and infinity. What is an impact then? Plus, the studies you are citing are not the most recent studies or reviews on aggregate LCAs. For instance, Braga et al. 2017 used derived models

L82: “paving road sublayers”: I do not know if it is advised to use common language only. Maybe you would like to specify which layers, according to pavement design vocabulary. Here I believe you are talking about subbase courses. By using non-specific language only, you are understandable by non-experts in infrastructure, what is good, but it gives a sense of lack of knowledge in infrastructure when experts read such a sentence.

L82-83: “rather than in higher-grade uses like structural components requiring high-quality concrete”: I believe you are first talking about asphalt concrete (made of 95% of aggregates, that represent most of the roads in the world), then maybe concrete (representing a small part of the pavements, but you will not have low quality concrete for roads anyway).

L3-84: “Sustainable management of these resources is a complex task hindered by a lack of comprehensive data”: please be specific about what you mean, it could be read as a common place with lack of substance.

L85: “Obtaining timely statistics for aggregates is challenging”: statistics about what? Please specify.

L94-95: “structural changes in greenhouse gas emissions”: about resource? Aggregates? I do not see the link here with the surrounding text.

L101: “Research on the future demand and supply of aggregates in China is scarce”: but you are addressing the period 1978-2050. So maybe adapt the sentence to justify why you also considered past years.

L110: “foster sustainability”: again, I think it would be clearer if you define what you mean by sustainability in your specific study.

L115: “that incorporate the circular economy’s core principles of Reduce, Reuse, Recycle”: please add a reference.

L101-116: the objective of the research is not clearly expressed.

Table 1:
• the source of examples are unclear: is it from ref #36, or explained in SN? Is the time horizon always 2050 (example #1)? If yes, specify in the title of the column, or in each suitable example (e.g; “it will drop from a baseline of 50.2 m² to 40.1 m².” misses a time horizon).
• “Lifetime Extension”: is it a credible scenario, considering the impact of climate change on infrastructure and buildings, under SSP2?
• In general in scenarios: did you incorporate impact transfers / feedback loops between material quality changes brought by including more recycling byproducts,/ using lightweight design and consumption changes? Example: to reduce the material intensity of final uses, I need to substitute aggregates by other materials, what will transfer environmental impacts on other commodities.

L124-126: “This decrease is attributed (…) as well as potential demographic change”: we do not know if there is a demographic change, and the attribution to demographic change is a possibility but unclear?

L125: “the saturation of the construction industry”: I do not understand what it means.

L131-132: “Significant demand declines are anticipated for both buildings and infrastructure; by 2050, under the All Measures (AM) scenario”: please remove semi-colon

Figure 2: the choice of the scale in the legend is questionable (7, 1 or 0.3 Gt: why these choices?)

L248: “exceeded 23 t/cap”: per year, on on the period 2016-2020?

L257: “they ranged from 147.4 to 360.1 t/cap”: you had 2 significative digits, rounding the result to the tonne on L248, now you have 4, rounding the result to the decimal… Pick a number and stay consistent when given your results.

L374-381: “The primary challenges of the sand and gravel crisis encompass environmental impacts related to water bodies, effects on biodiversity, and socioeconomic issues. (…) developing countries need to engage in scientific evidence-based modeling to evaluate these factors. (…) conducting a material flow analysis is foundational to this scientific evidence-based modeling”: you need to close the loop of your argument (and this is a general comment for the article). Why is MFA foundational? Because it can allow to calculate the different sustainability metrics at the regional scale based on the different resources produced/consumed, depending if we have a production or consumption-based approach. Example; you have the LCA results of different types of aggregate productions, you know the amount that I produced/consumed => you can calculate the total environmental impacts, and evaluate mitigation strategies. You need to explicit that (more synthetically than here, but your readers will not read your mind).

L391-393: “we conclude that robust, evidence-based policies and regulations are essential to ensure sustainable management and prevent overexploitation and a sand crisis.”: don’t you think it is a bit of a common place? “. This sentence is equally true, I believe: “we conclude that robust, evidence-based policies and regulations are essential to ensure sustainable management and prevent (whatever is negative from a sustainable point of view)”. You can make a better, more specific conclusion of your discussion section, based on your analysis.

L396_397: “We referred to China’s standards60,61 and international reports62 to define the aggregate resource in our model”: okay, but be sure the vocabulary is not specific to China’s standards, and easily understandable by non-Chinese readers”.

L488-494: “This curve is derived through logistic regression analysis and connected to future per capita GDP to estimate future per capita stock.”: you wrote earlier that there was a decoupling between aggregate consumption and GDP (l269-274): isn’t it contradictory?

L496-498: “Lifetime distributions for these uses were devised based on local standards and insights from developed economies..”: we can expect lifetimes to be a key parameter of your results. Can you specify more (or tell me where you mentioned) the lifetimes you used? I found some past lifetimes in the excel spreasheet, that seem relatively short (maybe due to regional differences between China and the rest of the world), and I did not see the distribution parameters selected, neither the specific sources of the lifetime consideration, or prospective lifetimes in the different scenarios (do they only change in the lifetime extention scenarios?). Especially, what is derived from standards, and from “insight from developed economies”, and what are these insights?

Supplementary material

General comments:
• an illustration of your method would be welcome, as well as a table with your variable names, as they are very numerous (MF X.Y, lambas, sigmas, etc.).
• A synthesis of how the model works in general would also be more than welcome. I personally had a hard time trying to understand your methodology, and I still do not have a clear idea of what has been done.
• I also believe you did not explain all your variables (e.g., mu, sigma): please double-check.
• Please place the figures as close as possible from the text where you discuss them, it eases the reading

L262: “"China Resource Comprehensive Utilization Annual Report" and expert consultations”: these sources are important to assess how credible are “the utilization rates of aggregate waste from concrete parts of residential construction, waterworks, and processing waste”: please provide the specific references.

Section 1.1.2: some elements would be interesting to set the table in the “main” section of the article (ref 6-8) about previous research, and their methods.

L595-598: “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.”: I do not understand this part of the model, what do you mean by “as identified in the demand-side”?

L625: “as detailed in Chapter 3”: I do not see any reference, which chapter 3 are you talking about?

(Remarks on code availability)
We did not see any code, notebook, or accessible calculation, but we had a look at the excel spreadsheet with the key parameters values. The values are clearly reported, but not standalone. Lifetime expectations seem quite short.

Reviewer #3

(Remarks to the Author)
The manuscript models various scenarios for the future stocks and flows of aggregates in China. Given China's role as a major consumer and producer of aggregates, this study holds global significance. It is striking to see the evolution of China's aggregate supply and demand, as it reflects an increasing substitution of natural aggregates with crushed stone, with the model's "All Measures" scenario indicating a potentially significant contribution from recycled aggregates in future supply. There is increased awareness of the urgent need to address the global sand sustainability crisis, and China has demonstrated commitment to this objective, as reported by the authors' work.

A recent comprehensive study by The University of Queensland and the University of Geneva [1] has identified China as the largest market for ore-sand, a purpose-made aggregate generated as a co-product or by-product of mineral ores. Vale's Brucutu mine has been the first successful case of ore-sand production at an industrial scale in Brazil. Researchers proved that Vale's sand has a lower environmental footprint when compared to traditional sand sources such as river sand or manufactured sand [1]. Furthermore, a 2022 report by the United Nations Environment Programme (UNEP), cited by this work's authors [2], has introduced ore-sand as an alternative source of aggregates at scale and, therefore, a promising solution to the global sand sustainability and mine tailings crises.
Depending on the ore body characteristics and technologies employed, ore-sand may have potential advantages compared with sand sourced from recycled materials (e.g. from construction and demolition waste), such as better control over product quality (e.g., the avoidance of contaminants in the product), enhanced workability, strength, and durability, lower production costs (due to fewer comminution infrastructure requirements and savings in mine waste management), and possibly greater consumer acceptance of an engineered material versus recycled waste. These and other potential benefits could position ore-sand as a crucial future resource for sustainable construction in China.
In their current study, the authors have chosen not to address ore-sand as a future resource option. Instead, they explore other circular economy strategies, such as reducing the extraction and production of aggregates through enhanced use of the built environment. This includes optimising material intensity, extending the lifespan of buildings and infrastructure, increasing the recyclability of construction and demolition waste (CDW), and combining these measures. While these strategies are valuable and complementary, omitting ore-sand as a potential solution seems to be a significant oversight. The authors have adopted a broader definition for manufactured sand, which appears to consider fine aggregates repurposed from tailings and waste rock; this is, however, distinct from ore-sand [1]. I recommend that the authors expand their conception of the circular economy by incorporating an analysis of ore-sand as a viable alternative for sustainable sand sourcing in China and other regions (e.g. through exports). This inclusion would provide a more comprehensive understanding of circular economy transition possibilities in China, as the manuscript title claims.

Additionally, the manuscript's reference to "circular development" as a scenario focused on recycling should be revised. Recycling is traditionally positioned near the bottom of the waste management hierarchy, representing an end-of-pipe solution within a linear system. In contrast, by incorporating innovation and circular economy principles from the design perspective (i.e., designing out waste rather than designing with waste [3]), as in ore-sand co-production or by-production, it is possible to substantially increase the efficiency of using mineral (and other) resources and, therefore, significantly reduce the impacts associated with mine waste and the supply of aggregates from conventional sources (e.g. from rivers or quarries). In this sense, I recommend that the authors reframe the "Circular Development" scenario as "Improved CDW Recycling" or a similar term to accurately reflect the strategy's nature within the waste management solutions hierarchy.

In conclusion, this manuscript could benefit from a broader perspective on sustainable aggregate sources, particularly by integrating ore-sand into its analysis. By considering this gap more carefully, the authors can present a more robust and forward-thinking evaluation of circular economy strategies in China's aggregate context.

References
[1] Golev, Artem, Gallagher, Louise, Vander Velpen, Arnaud, Lynggaard, Josefine R., Friot, Damien, Stringer, Martin, Chuah, Stephanie, Arbelaez-Ruiz, Diana, Mazzinghy, Douglas, Moura, Luanna, Peduzzi, Pascal, and Franks, Daniel, M. (2022). Ore-sand: A potential new solution to the mine tailings and global sand sustainability crises: Final report. Brisbane, Australia; Geneva, Switzerland: The University of Queensland; The University of Geneva. https://doi.org/10.14264/503a3fd
[2] UNEP 2022. Sand and sustainability: 10 strategic recommendations to avert a crisis. GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland. https://www.unep.org/resources/report/sand-and-sustainability-10-strategic-recommendations-avert-crisis
[3] https://www.ellenmacarthurfoundation.org/topics/circular-design/overview

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)
The paper is generally good and presents new understanding of recycled aggregate life cycles in China. I appreciate and comment the authors' hard work but suggest some improvements are required. I have four main comments and provide line-specific comments thereafter.
1. The supplementary information is substantial and proper understanding and scrutiny is difficult with the manuscript alone. Furthermore, some information within the supplementary information cannot be properly studied in their current format. Figures S28-S33 (the results of the uncertainty analysis) are too small to read.

2. The authors discuss assumptions related to aggregate stocks and flows in the modelled scenarios, but justification of the dynamic MFA model parameters appear to be lacking.

a) Log-normal distributions are assumed – a choice which, though common practice, is not explained, and alternatives are not discussed. Related to this is the uncertainty analysis. Here it would be good to explain why normal distribution and not the same log-normal distribution is used in the Monte Carlo simulation (parameter fluctuations).

b) It would be useful to include justification of parameter choices or some insight into their feasibility. For example, the extent to which building/infrastructure lifespans can be increased in China.

3. The discussion on absolute decoupling of aggregates and GDP over the period of 2016-2020. Some figures appear to contradict the authors' suggestion here.

4. Finally, I feel that the authors must better explain and justify comments made relating to environmental impacts and sustainability. These are important but often mishandled aspects of circularity and sustainable resource management.
//
Detailed comments by line
//
Line 33 It is the extraction/use of aggregates that pose environmental challenges not the aggregates themselves.
Line 36 Is it worth including a comment on the variation in aggregate demands peaking at the local scale compared to the national scale?
Line 38 I have an issue with 'we find' here as the shift from natural to manufactured aggregates in China is documented prior to this study, e.g., Z. Ren et al. (2022) (https://doi.org/10.1016/j.resconrec.2022.106173) as cited on line 335: 'China has shifted from natural to manufactured aggregates to meet high demand4'.
Line 40 This is the only use of 'recycled flows' in the manuscript and the only recycled flows in Fig. S3 is 'recycled aggregates'. Perhaps, '… availability of recycled [aggregates]' instead, or re-work the sentence.
Line 41 The implications of the results are a little vague.
Line 53 Feel free to ignore, but something like, 'In China, each cubic meter of concrete typically contains 1.8 tons of aggregates.', might be clearer.
Line 55 'For roads, between 4,000 and 30,000 tons…' may be clearer than '4 and 30 thousand tons'.
Line 56 As above, '…70,000 – 120,000 tons per kilometre'.
Line 62 Low awareness of what exactly?
Line 65 Clarify that the 'alternatives' are alternatives to sand as the previous sentence ended on waterbody extraction (i.e., extraction / an extraction technology). The topic changes back to sand on Line 65.
Line 66 '…offer solutions'   'are more sustainable and less environmentally impactful alternatives…' ?
Line 67 Clarify what 'industrial inputs'.
Might be useful to include reference to ecological/ecosystem management practices or their application in this context.
Line 68 I don't believe aggregates have 'distinctive environmental impacts' as LCA has pre-defined impact pathways depending on the life cycle impact assessment method applied, with potential environmental impacts at the endpoint.
If the sentence means to say the potential environmental impacts of traditional and alternative aggregates are different, this can be used to improve 'offer solutions' on Line 66.
Line 71 Some regions globally?
Line 72 Clarify how aggregate shortages lead to environmental and social impacts.
Perhaps replacing 'as well as' with 'which drives' – for example – would be sufficient.
Line 74 Great point – an important limitation for aggregate supply.
Line 78 The terms 'buildings' and 'infrastructure' in this paper are explained in the supplementary information (Table S1) but it might be useful to clarify the terminology here.
Line 79 Include reference for limited use of recycled aggregates globally.
Line 79 Great point about the restrictions of standards, etc., when trying to re-use aggregates especially in high-quality concrete.
Line 85 Timely   contemporaneous ?
Line 88 Add reference for the 'boom'
Line 93 Reference for '…nearly half of the global aggregate usage.' ?
Line 93 Add date (year) of the peak and decline. Something more quantitative than 'recent'.
Lines 97 Consider rewording as 'it' here is 'aggregate consumption', from the previous sentence. Rates of… ?
Line 101 Clear research motivation – good
The paper focuses on the production and use of recycled aggregates.
Line 106 Refer the reader to the supplementary map that shows China's provinces (Figure S2)?
Line 107 Flows and stocks?
Line 108 Generally, nice sentence about CHAMPS' potential impact.
Line 109 '…under [X modelled] scenarios' ?

Line 110 '[Greater] sustainability' maybe?
Line 112 Five not four strategies are listed: IU, LD, LE, CD, and AM.
Are these 'strategies' the aforementioned 'scenarios' ?
Line 115 IU, LD, LE, and CD incorporate only one R. Maybe 'aspects of the circular economy's core principles…' or similar.
Line 118 Tell the reader where in the Supplementary Notes to find the full specs.
Table 1 In the LD entry: '… used per unit of final use.'
Would 'per functional unit (e.g., one house)' be a useful alternative here?
Line 126 Ref 37 check ###
Line 128 Various scenarios? [the modelled scenarios]?
Lines 131 - 134 I think the ; and . are errors that confuse this summary of results.
Line 136 Remove 'with estimates ranging' ?
Line 139 Nice point about changing trends in asset investment.
Line 147 Imminent demolition? When are buildings/infrastructure expected to be at end-of-life?
Line 153 Is this saying road related infrastructure will contribute 39% of total outflows (construction waste?) by 2050? This could be more explicit, if the word count allows.
Line 154 Good point
Line 155 The authors suggest recycling CDW can alleviate environmental impacts.
I think this is instead 'can mitigate environmental impacts (of [primary] aggregate extraction]'.
Figure 1 Can the figures be started at x = 0, y = 0 as there are no negative y-values in A, B, and C ?
The current format is likely an aesthetic choice.
It would be useful to have keys in all panels or make clear if that in Fig.1B applies to Fig.1A and Fig.1C. Perhaps describe the colours in the caption to make the figure stand-alone?
Line 166 A clear subheading will clarify the framing of the subsequent text.
'Recycled aggregates [can] bridge the circularity gap [in China]'
'[The use of] recycled aggregates to bridge the circularity gap [in China]'
Given the first paragraph references past work/results, perhaps the second edit is closer to the authors' intended meaning?
Line 170 Rather than 'evolution', how about 'transition from sand and gravel to crushed rock'?
Line 178 Environmental impacts here are again vague / the sentence could be improved.
Line 181 Consider rewording 'the use of outflows in circularity'.
E.g., 'the [circular use] of outflows' or 'the use of outflows for circularity' ?
Line 182 Which scenarios show this?
Line 183 Am I right in saying the 'supply of recycled aggregates' here is their availability / their return to market but not necessarily their use?
Line 186 The data is in Figs S5-S8 but guide the reader to the discussion/analysis of those results.
Line 193 Clarify in the text what comprises 'total waste' (as in Fig. 2D) ?
Line 199 Again, benefits re environmental impacts and sustainability are mentioned without adequate (in my opinion) explanation. There is no reference here even.
Lines 205-211 There is a mixture of mass and percentage values. 55% decrease then 6.0 Gt reduction then 4.5 Gt 'surge'. Consistency would enable comparison.
Figure 2 I'm not sure Fig.2A shows recycled aggregates surging in the forecast section, especially compared to the increase shown for crushed rocks between 2000 and 2010. Perhaps a less emotive word?
Fig. 1B – why are only three dates shown across the 1978-2050 scope?
Fig. 1D is nice – a good use of Sankey – but it could be neatened up a little (editorial comment as the information is conveyed as-is).
Line 222 Highlights [differences] in… ?
Lines 222- 225 Nice!
Lines 227-231 I think this is the only use of the terms 'investment-driven' and 'infrastructure-driven'. Investment-driven is more intuitive, but infrastructure-driven – demand driven by infrastructure needs (I think) – needs further explanation.
Line 239 Is there a reference or specific result(s) that confirm differences in demand drive the disparity?
Line 257 Re-structure sentence to remove 'they', e.g., 'Per capita stocks ranged from…'
Lines 260-261 Here, 'lead to' suggests causality - is this a confident assertion made from the results? Are other (interdependent) factors at play?
Alternatively, change 'lead to' to 'contribute to' or similar.
Line 269 GDP increases across all provinces in Figure S24 and Figure S25 and total aggregate demand in Figure S24 and aggregate inflows in Figure S25 have a more gradual net increase. Yes.
It might be prudent to clarify relative decoupling here.
Line 271 Consider some adjustment around, 'as the economy…', to distinguish the two points made: (i) the essential role of aggregate stock in supporting development, and (ii) the move away from rapid stock growth now that the economy is (suggested by decoupling and steadier GDP) at a point where existing infrastructure/buildings are sufficient.
Line 272 Which provinces are the authors referring to re absolute decoupling? No figures or data are referenced here.
The authors provide a good definition of absolute decoupling here.
However, the plots in Figures S24 and S25 do not all show a decrease in aggregate demand between 2016 and 2020. Guangdong and Guizou (in both Figs S24 and S25), for example.
Perhaps the authors mean that at points within the period 2016-2020, there is some absolute decoupling?
Further clarification is required here.
Line 278 Demographics can suggest more than population (number of individuals). Do the authors mean to include population characteristics (e.g., age, race) here?
Line 292 Potentially meeting – what are the requisites and barriers?
Line 296 I'm not sure about, 'waste generation is expected to exceed demand' – is there a demand for waste ? For recycled

aggregates?
Line 297 Does ‘excess waste’ suggest a shift towards more sustainable, circular models ?
Again, what is the likelihood of this and its requisites/barriers ? It is possible that excess waste results in increased landfill, especially if usable waste (recycled aggregate) is generated far from potential users.
Figure 3 Add a key / explanation in the caption.
Figure 4B This may simply be my inexperience with this plot, but I find it difficult to understand what the widths convey given there are no x-values.
Why only 2020 and 2050 across the modelled period of 1978-2050?
Line 319 ‘…often [reflects] levels of…’ maybe?
Line 325 Some words missing around ‘All Measures’
Line 338 Check wording of ‘to mitigate sand scarcity sustainability’. Just ‘sand scarcity’ maybe? You want to mitigate scarcity and achieve sustainability.
Line 340 Great point again, yes.
But for context, is this what China is moving towards: high-value construction?
Line 340 More policies? Better policies?
Previously the authors mentioned policies re a shift from natural to manufactured aggregates.
Line 347 Would the technology ‘increase the market’s acceptable of recycled aggregates’ or rather increase capacity to produce recycled aggregates to satisfy e.g., material/building standards?
Line 348 Why tax incentives first and foremost rather than aforementioned policymaking?
Provide examples where taxation has benefited market acceptance of recycled aggregates, to justify this suggestion.
Line 351 ‘Green practices’ is vague (green washing term). Consider expanding upon this point and clarifying whether the use of recycled aggregates is a green practice (based on environmental impact mitigation, economic circularity, etc.).
Line 355 This final ‘future work’ sentence feels a bit vague/an add-on. Can it be linked to this research topic more specifically?
Lines 358-359 The align comment: are the authors meaning that their results agree with the previous study’s findings at the global scale?
The topic sentence is about crushed stone production but the paragraph continues on about aggregate demand.
Line 361 Commas: natural sand, gravel, and crushed stone
Line 363 Due to peak?
Line 364 It’s   it is (avoid contractions)
Lines 364-367 Link to previously identified issues with aggregate supply?
‘Given X, Y, and Z associated with…, it is crucial to…’
Line 367 While China’s transition to manufactured aggregates provides a model for other developing countries to follow, there will be other examples worth mentioning, and location-specific requirements that might make other transitions more practical in the developing regions.
Line 378 This is true for all countries (and local areas given the importance of regional perspectives, per Line 374), not just developing countries.
Line 380 Clarify and evidence how Material Flow Analysis (MFA) contributes to ‘standardisation’ and ‘regulation’ within developing countries.
MFA can improve understanding of stocks and flows but cannot by itself provide data on potential impacts of aggregate extraction/use/etc – this requires e.g., LCA.
Line 384 Yes, excellent point
Line 385 ‘GIS data’ rather than ‘GIS perspective’?
Line 387 Are the authors claiming the locations of aggregate stocks were not known prior to this study?
Is the statement that GIS enables temporal data to be aggregated for analysis the CHAMPS?
Lines 387-389 Again the ending feels a bit vague / not as punchy as it could be. It could be linked to the development of CHAMPS more.
Lines 391-393 Tax incentives are no longer suggested – omission or change of heart?
Line 396 Ref for ‘no unified definition’?
Line 400 Rephrase this sentence – I don’t think it quite makes sense/can be clearer.
Line 406 Would be good to have a reference for recycled aggregate quality can match that of virgin aggregates – especially given the aforementioned issues with separation/re-use in high-quality infrastructure.
Line 423 Consider restructuring this bit.
Tailings are omitted here because their rate of use is negligible in China/this study?
Line 427 Is there scope to put the framework (Figure S3) into the main text ?
Line 428 Can the five stages be presented more clearly or as bullet points?
It currently looks like there are seven not five items.
Line 448 SSP2 is first mentioned here. Add a reference or explanation.
Line 456 Reference is this is an established analysis model type, or refer the reader to supplementary discussion – this may be the later referral on Line 460.
Line 464 Adds   plus (i.e., +)
Eqs 1, 2 Define coefficients / nomenclature
Line 469 Justify the decision to use the log-normal distribution function in this study. Even if ‘established best practice’.
Eq. 3 Define coefficients/nomenclature
Line 478 Established social metabolism model is mentioned. What is the tailored social metabolism model for the future scenarios?
Eq. 4 The term ‘saturated stock’ is used once in the SI and once in the main text (here, Eq. 4). This term needs to be explained along with the other nomenclature in Eq. 4.
Line 490 Is ‘densities’ here describing probabilistic (log-normal) distributions of aggregate flows?

Line 492 Sounds good but add a reference the fact economic growth typically follows an s-shape curve linking to the sentences on Lines 493-494.
Line 517 The reader is referred to Section 2.4, Supplementary Notes, for details on specific parameter settings.
Following this re housing lifespan, there appears to be a need to better justify assumptions or at least give some insight into the likely future lifespan of buildings/infrastructure and their upper limits. Are there general limitations? China-specific limitations?
This is lacking, e.g., '…this study assumes a 90% extension in the service life of new housing constructions from 2021 to 2050, based on the 2020 benchmark.'
I extend this comment to all assumptions/parameters in the scenario analysis.
Line 553 Why is a normal and not log-normal distribution used for the uncertainty analysis?
Lines 557-559/Figs. S28-S33 The uncertainty analysis plots are too small / hard to read.
Line 592 Supplementary information section could be restructured to make it clearer, naming the files and their contents.

(Remarks on code availability)
I took a look at the code but coded models are not where my experience lies. I do not have experience with R and hence do not have the environment to run the code. Therefore, my observations do not include whether the code operates fully.

The README text clarified that the code is not provided in its entirety, which hinders repeatability.

The equations presented in the manuscript appear present within the code, suggesting it is a functional and corresponding codebase for the CHAMPS model.

I did not locate any Plot() commands suggesting that the codebase does not output visual results and that figures must be created by the end user using output data.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have made great effort to revise the manuscript, it is easier to understand than the previous version. Following are some suggestions to improve the paper:
1) We find that China's aggregate demand peaked around 2015 along with a supply side shift from natural to manufactured aggregates. Is the aggregate peak and the shift happened at the same year?
2) Total demand is projected to decline to ~50% of 2020 levels in circular economy scenarios. Which year is this total demand? is it 2050?
3) I wonder if there is study about recycled aggregates globally? how is the technology? how much is the cost? Currently the recycled aggregates in China is not so popular, most of them leads to landfill.
4) in line 50, billion tons (Gt, Gigaton) may be better as billion tons (Gt).
5) Around 1.1 trillion tons of non-metallic minerals was extracted globally for construction between 1970 and 2019. This is equivalent to removing a 3–4-millimeter layer over the Earth's entire land surface (see Supplementary Notes for calculation). Is there any reference for this?
6) In recent years, China has historically consumed around half of global aggregates extracted.what does this mean? China consumed around half of global aggregates extracted historically, or only in recent years?
7)Building one square meter of a building requires 1.2 tons. This sentence needs to be revised to make it clear.
8) in line 63, concrete-based construction has led to enormous demand for aggregates, for should be of.
9) in line 66, at a local level, what is a local level? provincial level or village level?
10） is sand really common pool resource?
11) the introduction maybe too long, it would be good to make it concise.
12) the maps lacks basic component, like the scale bar and the north arrow, for example, figure 4.

(Remarks on code availability)
The code can be used and the results of the paper are reproducible.

Reviewer #2

(Remarks to the Author)

(Remarks on code availability)
I have not been able to open the code (looping while downloading)

Reviewer #4

(Remarks to the Author)
I (Reviewer 4) was thorough in my previous review. I thank the authors for their patience and for being thorough in their revision of the submitted manuscript and in their responses to my comments. The authors addressed my concerns, and their

submitted manuscript is good; the limited number of minor comments below reflect that.

Specific comments:
Line 469 Add a reference to support the statement, ‘China's success in transitioning from natural to manufactured aggregates (crushed stone) through strong policy guidance demonstrates the effectiveness of targeted regulations in mitigating these impacts.’

Line 77 Consider removing ‘and’, i.e., ‘Supply-side changes are important. Less environmentally impactful resources include…’, or similar restructuring.

Line 80 Consider reworking this sentence. I provide an example here of what I think might work better. ‘However, [crushed rock] and [ore sand] are not without environmental impacts. Their use requires strict management, but their regulation is more feasible than that of [natural] sand and gravel, which are widely extracted illegally.’

Line 169 ‘…coming future’ ‘…near future.’

Line 341 ‘…under All Measure scenario,’ ‘under the All Measure scenario,’

Line 344 It might be worth adding a brief statement/caveat about the possibility/practicality of interregional redistribution of surplus waste aggregates.

Line 590 I think there is still something ‘off’ here, requiring a tweak.
(i) Would ‘stocks [and] densities’ rather than ‘stocks or densities’ be correct?
(ii) Place the parentheses immediately after ‘densities’ as the examples relate to densities (demographics and factors influencing demographics) rather than stocks directly.

Line 670 Re my codebase comments: the authors explain, ‘The core functionalities and models, including the CHAMPS model of one region, are fully implemented in the code we provided. The additional code for plotting and visualization, which can be quite complex and specific to our setup, is not included as it was deemed non-essential for replicating the model’s results.’
Thank you for clarifying. I also note that the Data Availability section explains that requests for resources will be fulfilled by the lead contact. Further requirements here are a decision for the journal.

Line 675 Remember to add the codebase information to the Code Availability section prior to publication.

(Remarks on code availability)
I have no additional comments. Whether the partial codebase is sufficient is at the discretion of the journal.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The manuscript has largely improved than the last version. I don't have more comments on this.

(Remarks on code availability)
The code is usable.

Reviewer #2

(Remarks to the Author)

(Remarks on code availability)
I uploaded my comments in a file

Version 3:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
See file

(Remarks on code availability)

Response to Reviewer #1:

Sand is the second most exploited natural resource in the world after water. Sand sustainability has become an important topic in recent years. As the demand for sand resources is increasing, meeting the demand and reducing its negative impacts are critical. This paper takes China as an example and examines the potential of recycling in sand sustainability. The authors have found that recycling can play a very important role in the future supply of sand. The results can have great implications for construction and infrastructure development. The results of this paper are trustworthy, and the methods are innovative. It is the first to explore the potential of recycling in balancing the sand supply and demand. The methods provided in the paper are reproducible. Following are several suggestions to improve the paper:

Response:

Thank you for your positive comments and insightful suggestions. These have greatly contributed to improving the quality of our manuscript. We have carefully addressed all the points raised and made the necessary revisions accordingly.

(1) The authors provide much information; they cover the transition from natural aggregate to manufactured aggregates, recycling aggregates, provincial disparity, and sand supply vs. sand demand. However, the main story is not clear enough.

Response:

Thank you for the suggestion. The evolution of sand and aggregate use in China is indeed a story of supply and demand, and we have structured the paper to highlight key points:

Demand Dynamics (Peaking and Declining Demand, with Rising Future Waste):

- China's aggregate demand peaked at 18.8 Gt/year in 2015 and is projected to decline significantly post-2020, stabilizing around 9.5 to 11.1 Gt/year by 2030.
- This decline is driven by the saturation of the construction industry, demographic shifts, and the socioeconomic impacts of the COVID-19 pandemic.
- By 2050, demand is expected to range between 9.2 and 12.4 Gt/year, marking a reduction of around 50% from peak levels.

Supply Transitions (Recycled Aggregates can Bridge the Circularity Gap):

- Historically, China relied on natural aggregates (sand and gravel) sourced from rivers, but there has been a shift toward manufactured aggregates (crushed stone), now accounting for 80% of the total supply.
- Recycling is projected to play an increasingly significant role, with recycled

aggregates expected to comprise 48% of the total supply by 2050 under the All Measures scenario.

- Circular economy strategies, including lightweight design and building lifetime extensions, are critical for reducing reliance on primary aggregate extraction.

Subnational Disparities (Subnational Disparities and Shared Saturation Trends):

- There are substantial differences across provinces in aggregate demand and supply, shaped by each region's economic development, construction demand, and resource endowments.

- Coastal provinces like Zhejiang and Jiangsu show higher per capita aggregate demand due to rapid urbanization and economic growth, while regions like Guangdong have lower demand relative to GDP.

- Less-developed areas such as Tibet and Guizhou continue to experience high aggregate demand due to their ongoing infrastructure development needs.

Policy and Environmental Implications:

- The transition toward more sustainable aggregate supply and increased recycling will require strong policy support, including economic incentives, standardization of recycled aggregates, and stricter regulations on aggregate extraction.

- Recycling demolition waste can reduce the extraction of virgin resources while mitigating the environmental impacts associated with the mining of primary aggregates. However, for this to align with China's broader circular economy goals, related industries and infrastructure need to be fully in place.

- Policymakers will need to address the environmental impacts of both primary extraction and the growing volume of construction and demolition waste, while also managing regional disparities in aggregate use.

We emphasize that, as sand and aggregates are resources that exhibit typical characteristics of the "tragedy of the commons," both the transition from natural sand to manufactured aggregates and the future development of a circular economy, including related industries, will require strong policy interventions. We conclude the paper with this message. We hope that this study, based on China's developmental experience and quantitative analysis, can serve as a reference for other countries.

(2) Sand and gravel supply is not only determined by the resource itself, recycling rate, but, most importantly, by policies, resource governance, market, and illegal mining (See Lamb 2023, EXIS. There are some more deep insights). The supply-side analysis in this research is not well established; for example, the provincial government issues the maximum available mining volume for the main rivers annually in Guangdong Province of China. However, the cities have their mining plan for the small rivers.

Besides, does the supply-side model include illegal sand mining? If not, how does this affect the results?

Response:

We thank you for these comments and the reference.

As you noted, the supply of sand and gravel is shaped by policies, governance, market forces, and illegal mining. In China, local governments play a key role. For example, provincial governments like Guangdong regulate major river mining, while cities manage smaller rivers. In regions like the Yangtze River basin, river sand dominates, while Guizhou focuses on manufactured aggregates from quarries.

In response to your concerns regarding the supply-side analysis, we have structured our research around two key phases of aggregate supply transformation:

(1) The historical transition from natural sand to manufactured aggregates. During a period of rapid economic growth, the depletion of easily accessible natural resources led to a shortage in supply. This shortage, along with rising prices, illegal mining, and environmental degradation, created significant social and environmental pressures. In response, government policies and these pressures drove the shift toward manufactured aggregates.

(2) The transition from manufactured to recycled aggregates in the future. In our scenarios, our calculations suggest that aggregate demand in China will decrease, while waste aggregates will increase substantially. Based on current technological developments and policy frameworks, we have developed a detailed scenario for circular development. This scenario is built upon a comprehensive analysis of waste generation, recycling rates, and the pathways for material circulation. We have revised the Methods part to make the two supply-side analyses clearer.

Regarding illegal sand mining, we recognize its historical significance in China. While illegal extraction was widespread in the past, a nationwide crackdown on organized crime since 2018 has largely eliminated this issue in the aggregate industry (https://press-files.anu.edu.au/downloads/press/n12044/pdf/ch11.pdf), with most actors transitioning to legitimate operations. Therefore, illegal mining is not included in our future supply-side scenarios. For historical data, we rely on well-documented sources, including industry reports and the literature, which account for supply complexities without isolating the effects of illegal mining separately.

Based on your suggestions, we have revised sections of our discussion and cited this reference accordingly:

> *We emphasize that the sand crisis is not a simple global issue, but rather a local one, making regional and local studies essential. The crisis is driven by sudden imbalances between demand and natural resource availability. However, it's important to recognize that how this crisis is framed can oversimplify the complex political, social, and environmental dynamics at play, potentially leaving out important perspectives and solutions17. The direct and primary challenges of the sand and gravel crisis include environmental impacts on water bodies, effects on biodiversity, and socioeconomic issues stemming from mining activities,*

including illegal extraction20,70.

(3) "China has shifted from natural to manufactured aggregates to meet high demand." do the authors have any data to clarify this transition?

Response:

Thank you for your question. We have collaborated extensively with the Chinese aggregates industry and have obtained this data from the China Aggregates Association (referencing reports from the association: http://en.zgss.org.cn/industry/d_619c8fb50d3abc00a4143aa6.html). This information is also reflected in our previous work (https://www.sciencedirect.com/science/article/pii/S0921344922000210). Additionally, a recent article further supports this result (https://www.nature.com/articles/s41561-024-01501-6). Our data shows that from 2005 to 2018, the share of manufactured sand and gravel in China's total aggregate consumption increased from 20% to around 80%.

(4) Diving deeper into the results, trends, and numbers the authors have mentioned is significant. Interesting results with explanations can help the readers understand the main findings better. For example, what's behind the "aggregate demand in 25 of the 31 provinces peaked before 2020, excluding some less-254 developed western regions and Guangdong" (Line 254-255). What drives the growth rate of stocks in most provinces is projected to be greater than 2% (Line 280-281, as well as this paragraph). What's behind "for buildings, the proportion of waste recycled and used for fillings is projected to increase from 12% to 66%" (Line 195-196); why, how, and what does it mean?

Response:

Thank you for your suggestions regarding these interesting results. We provide some explanations and discussions here.

For provincial peak dynamics, regions with underdeveloped economies have not yet fully developed and therefore have not reached their peak. For example, the consumption of aggregates in Guizhou Province was still on an upward trend in 2020, with a per capita stock of 202 tons per person, significantly lower than the top-ranking Jiangsu Province, which had 360 tons per person. However, as the country transitions to peak demand and enters a new stage of social development, these underdeveloped regions are also approaching their peak.

Second, the reason Guangdong has not yet peaked is primarily due to the relatively low demand for housing construction, and there is still room for growth in the housing stock. The reason for lower housing construction in Guangdong is partly to do with the fact that Guangdong is a large province, but wealth is mainly concentrated in the Pearl River Delta, particularly around Guangzhou and Shenzhen. The western part of the province is still less developed, and where further housing is necessary

Another reason is the province's economic development model. As referenced in our material footprint studies (https://www.pnas.org/doi/abs/10.1073/pnas.1903028116; https://www.sciencedirect.com/science/article/pii/S0921344923003257), The per capita building stock in Guangdong is smaller compared to more developed provinces like Jiangsu and Zhejiang, while it is similar to relatively less developed provinces such as Qinghai, Heilongjiang, and Shanxi.

We have made the following modifications to the text and placed the extended discussion in the SI section.

> *Overall, aggregate demand in 25 of the 31 provinces peaked before 2020, excluding some less-developed western regions and Guangdong, where economic development is mainly driven by consumption, and there are relatively large internal imbalances within the provinces (see Supplemental Notes 3.6 for extended discussion).*

In our scenario analysis, the 2% growth rate in stock during 2021-2025 is mainly influenced by historical construction demand and economic development. This marks a significant slowdown compared to the stock growth around 2015. In scenarios, under circular economy policies, changes in intensity coefficients and lifespan expectations are expected to drive stock growth towards zero or even negative levels. However, in the short term (2021-2025), it is challenging to fully capture the long-term patterns of stock. Additionally, economic data, sourced from the SSP scenarios, play a crucial role in stock evolution. Unlike flows, stock evolution experiences a longer lag. As a result, driven by ongoing economic development, the stock will largely follow its historical trend in the short term, with only slight deviations.

We have made the following revisions in the text accordingly:

> *From 2021 to 2025, under various scenarios, the growth rate of stocks in most provinces is projected to be around 2%, a decline from the nearly 6% observed during the peak consumption period around 2015. By 2035, the stock growth rate is expected to approach zero, with some provinces, such as Heilongjiang and Jilin, potentially experiencing slight negative growth.*

Regarding the phrase "for buildings, the proportion of waste recycled and used for fillings," it's a potential ambiguity and we would like to clarify. "Recycled and used for fillings" refers to two separate processes—recycling and filling—which might be interpreted as recycling followed by filling. In future scenarios, the amount of construction and demolition waste from buildings will increase, along with the recycling rate. As a result, both the volume of recycled waste and the amount utilized for fillings will also increase.

We have made the following revisions in the text accordingly:

> *For buildings specifically, the proportion of waste that is recycled and the proportion used for fillings are projected to increase from 12% to 66%. In future scenarios, the amount of CDW generation will grow, and with higher recycling*

rates, both the recycled volume and the amount utilized for fillings will increase accordingly.

(5) "Recycling of aggregate waste in China is expected to rise from 734 million tons (Mt) in 2021 to 4.5 billion tons (Gt) by 2050 under the All Measures scenario, increasing its share from 13% to 46% of total waste (Figure 2D)." Recycling aggregates have a market in China, and to make sure recycling aggregates are being used, technology is required to produce high-quality products at cheaper prices and people's acceptance. Except for these, have the authors considered that some concrete products have their maximum recycling aggregate ratio? Because too much aggregate recycling can affect the quality of the concrete.

Response:

Thank you for your question regarding the aggregate recycling rate.

Indeed, the recycling rate for aggregates can never approach 100%, and there will be differences in recycling rates depending on the type and use of the aggregates. Taking the limitations of the maximum recycling rate into account, we have set specific maximum recycling rates for different end uses in the supply-side part of the scenario analysis model. This is detailed in Tables S3 and S4 and is also reflected in the code we have uploaded.

Table S3 Future recycling rates of building demolished waste and construction waste under the circular development 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 circular development 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%

We have made the following revisions in the text:

Calculating the production of recycled aggregates is based on the outflow of aggregate waste generated from various stocks, as determined by the demand-side scenario analysis, and applying the set recycling rate. Assuming that the maximum recycling rate within a technically feasible range is reached in 2050.

(6) Has the research considered the trade between provinces? It can affect the material supply. How does the model deal with this? Have the authors considered international trade? How is that calculated in the model? As we know, Hong Kong imports a lot of sand from mainland China.

Response:

Thank you for your question regarding inter-provincial 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 (https://compass.onlinelibrary.wiley.com/doi/10.1111/gec3.12560; https://www.unep.org/resources/report/sand-and-sustainability-10-strategic-recommendations-avert-crisis), 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.

We have included an explanation of this point in the SI.

(7) The authors should consider using the word 'crisis' more carefully. "We emphasize that the sand crisis is not a global issue, but a local one, making regional and local studies crucial." (Line 374-375) As Lamb said, "Scarcity is political: who defines scarcity? How does this shape who is involved and what solutions are possible?" (Lamb, 2023) Is the crisis a short-term problem or long-term? What does the local sand crisis mean?

Response:

Thank you for your reminder regarding the use of the word "crisis."

This term is primarily referenced from the UNEP report (Sand and Sustainability: 10 strategic recommendations to avert a crisis). In this paper, the sand crisis refers to a series of issues arising from increased demand for sand due to economic development, such as the mismatch between supply and demand, the environmental damage caused by sand extraction, illegal activities fueled by the sand industry, and the disruption of construction projects due to supply tensions. These kinds of issues are common in most economies, particularly in developing ones.

Given the highly localized nature of sand and gravel, the sand crisis generally occurs in specific regions, which is also the main reason why this study focuses on sub-national, regional-level research.

We *thank* you *for* providing the meaningful article by Lamb (2023). Based on this discussion, we have made the following revisions and explanations in the text:

> *We emphasize that the sand crisis is not a simple global issue, but rather a local one, making regional and local studies essential. The crisis is driven by sudden imbalances between demand and natural resource availability. However, it's important to recognize that how this crisis is framed can oversimplify the complex political, social, and environmental dynamics at play, potentially leaving out important perspectives and solutions17.*

(8) For audiences from other countries, what does the Chinese story tell us? What are the differences between China and other countries?

Response:

Thank you for your interest in the "China story," which allows us to further highlight China's uniqueness.

First, after the reform and opening-up, China experienced rapid development, which also brought many issues, with the sand and gravel problem being a prominent one. Sand and gravel, as a cheap and easily accessible resource, had long been overlooked. However, with rapid economic and social development, a sudden supply shortage occurred, leading to a series of issues related to the sand and gravel industry. Currently, China is transitioning from rapid growth to high-quality development, aiming to resolve problems created during the earlier stages of growth.

In contrast, most Western developed countries completed their modernization in the last century, with long cycles of capital accumulation and infrastructure development, making the sand and gravel-related issues less prominent.

For developing countries like India and even those in Africa, China offers valuable lessons. On one hand, it is important to be cautious about the potential surge in demand for sand and gravel. On the other hand, early attention should be given to the sand and gravel industry, establishing relevant standards, regulations, and legal frameworks to ensure the long-term stable development of the industry.

Internationally, there is a common perception that China’s sand and gravel industry has caused significant environmental damage. However, over the past decade, the industry in China has undergone dramatic changes, with significant efforts made toward green mining. In the future, recycled aggregates will also have a large potential for development.

Therefore, we emphasize that, due to the "tragedy of the commons" nature of sand and gravel, strong policy intervention is crucial.

We have made the following revisions in the text accordingly:

> *Given the challenges associated with aggregate supply, including social and environmental impacts on natural aggregate extraction and rising demand, it is crucial to assess how urban development and the need for sustainable aggregate supplies will evolve in developing regions such as the Middle East, Africa, South Asia, and South America. These areas might become the main markets for aggregates in the future. China's transition to using more eco-friendly, manufactured aggregates (crushed stones) as a substitute for river and lake sand can serve as a valuable model for others. However, regional differences may require alternative approaches. It remains uncertain if there are sufficient and accessible rock quarries in every area to follow this model since transporting aggregates or rocks over long distances, whether recycled or extracted, is costly.*

(9) what is the story regarding the difference between the provinces inside China?

Response:

Thank you for your question regarding provincial differences. Concerning the disparities between China's provinces, the provinces with higher sand and gravel consumption are generally concentrated in more developed regions. Sand and gravel consumption can be further divided into that used for housing and that used for infrastructure.

Across the country, infrastructure stock levels are relatively consistent, while housing stock levels vary significantly depending on regional economic scale and structure. In wealthier regions, where population density is higher and industrial clusters are more concentrated and diverse, the stock of sand and gravel used for housing is relatively large. In sparsely populated and less developed regions, while the overall development is lower, the per capita stock/consumption of sand and gravel for infrastructure is often higher due to the lower population density. We have provided relevant explanations in the text:

For example, from 2016 to 2020, Guangdong's infrastructure-driven demand was around 3.2 t/cap, comparable to 2.7-4.2 t/cap in Zhejiang and Jiangsu, but its building-driven demand was only 16-43% (3.8-6.8 t/cap) of that in Zhejiang and Jiangsu (15.0-24.1 t/cap). Despite Guangdong's progress in infrastructure and buildings, its per capita aggregate demand remained steady at 7-8 t/cap from 2008 to 2020, reflecting an economic structure less reliant on construction.

…

Less-developed regions also had high per capita aggregate demand between 2016 and 2020. Xizang (Tibet), for instance, exceeded 23 t/cap, due to strong development needs for infrastructure and buildings, coupled with lower population density in 2020 (Figure 4D). Other less developed but rapidly growing provinces, like Guizhou, Yunnan, and Shaanxi, which had not yet peaked by 2020, saw high demand ranging from 12-18 t/cap (12 provinces in this range). Rest 16 provinces, including other relatively wealthy regions and those with long-standing stock accumulations such as Northeastern China, had moderate demands ranging from 7-12 t/cap.

On one hand, as the country's overall development gradually reaches a mature stage, sand and gravel demand in all regions is stabilizing. Even in less developed regions with weaker foundations, sand and gravel consumption has reached or is approaching its peak. On the other hand, we must remain cautious of the potential crisis of a sudden surge in sand and gravel demand in underdeveloped areas in the future, and it is important to regulate the local sand and gravel industry. Additionally, under the current circumstances, we should also be mindful of the issue of overcapacity in the sand and gravel industry.

From a future scenario perspective, more advanced regions, such as the Yangtze River Delta, may achieve closed-loop recycling of sand and gravel for specific end uses in localized areas. In this context, it is necessary to further develop cross-end-use and cross-regional recycling pathways. Based on the existing sand and gravel stock, early planning for the sand and gravel recycling industry is crucial. We have made the following revisions in the text accordingly:

Throughout China's development, affluent coastal areas have consistently seen higher demand than other regions, a disparity that has been exacerbated by urbanization and internal migration. However, as the country nears its overall peak demand, these wealthier areas are nearing saturation, and less affluent regions are also reaching their peak aggregate demand aligning the trend, albeit at lower levels. Given current uneven demand across the country we have to be alert to the problem of overcapacity of aggregate production as the demand is projected to decline. We should also be alert to the potential sharp increase in aggregate demand in underdeveloped areas to prevent the recurrence of "sand crisis" in the future.

(10) The authors also need to consider the feasibility of recycling sand. Currently, sand construction waste is always used in landfills, as the cost of recycling sand from construction waste is expensive compared to others. The authors can also include the cost-benefit of the recycling approach.

Response:

Thank you for raising this question. Regarding the issue of recycled aggregates, we consulted experts from the Sand and Gravel Association, as well as manufacturers of recycled aggregates and recycling equipment. Recycled aggregates are indeed more expensive than natural aggregates, especially due to the difficulty of separating construction waste during the production process. However, the cost difference between recycled and natural aggregates is not that significant, estimated to be within 10%, according to expert opinions.

Currently, recycled aggregates are widely used in concrete bricks. Experts in sand and gravel technology suggest that high-quality recycled aggregates can completely replace natural aggregates in concrete production. Of course, this would increase costs, but the feasibility depends on the specific case. At present, the main factor limiting the development of recycled aggregates in China is not technology, but rather a lack of market acceptance and policy support.

When market and policy conditions become more favourable for the development of recycled aggregates, technology will indeed become the key factor limiting recycling rates. However, according to our calculations, with the anticipated decrease in sand and gravel demand and the increase in waste generation, the volume of recycled aggregates, under achievable and reasonable recycling rates, would already be able to meet the demand for sand and gravel.

In the future, as technology advances, the production costs of recycled aggregates will surely decrease further. However, we hope that substantial changes in policy and market conditions will occur to promote the development of recycled aggregates.

We have made the following revisions in the text accordingly:

Boosting the market for recycled aggregates will likely require some mix of economic incentives (subsidy or tax reduction) for using recycled products, incorporating recycled materials in bid requirements, and promoting the standardization of reusable concrete components65. China's "green mine" policy promotes key strategies such as subsidies for intelligent operations, environmental protection, high-quality production, and effective management. It encourages large-scale ecological operations and the shift to a circular economy. Recognition programs and targeted incentives for innovators further support these goals66. Effective collaboration across technical, policy, and academic institutions will be needed to guide and monitor the development of a recycled aggregate market. If enough steps are taken the output of recycled aggregates can already meet most of the demand for aggregates at a recycling rate within a reasonable range in the future, according to our findings.

(11) Reviewer #1 (Remarks on code availability): The paper can be reproducible as the authors have provided code for CHAMPS, and the code is executable.

Response:

We thank your evaluation of the CHAMPS code.

Response to Reviewer #2:

(1) General. This article evaluates the aggregate consumption in China between 1978 and 2050, with a prospective scenario-based modeling after 2020. While aggregates are an important resource as showed in the “main’ section of the manuscript, we found hard to follow the logic of the “main section”, to be convinced by the conclusions of the article, by the scenarios, and we found the method extremely hard to understand, both in the manuscript and the supplementary materials. I am still unsure of what have been done, as some variables seem not to be explained from the equations of the SM. The objective of the study are not clearly stated to my opinion.

Response:

Thank you very much for your comments. We have made adjustments to the Methods and SI sections to present this relatively complex integrated assessment more clearly.

Our study is based on the numerous industry issues that have emerged in recent years within the sand and gravel sector (e.g., massive consumption, long-standing neglect, lack of regulation, over-exploitation, and supply-demand imbalances). Using China as the largest player in sand consumption, we developed the CHAMPS model to reveal the patterns of the sand and gravel industry within economic development. The goal is to provide quantitative support for policy-making and to analyze sustainable development pathways for the future of the sand and gravel industry. We provide an open model that can be used in other analyses.

Specifically, this study builds on thorough industry research and the theoretical foundations of industrial ecology to address the key challenges in the sand and gravel industry. The CHAMPS model generates results that answer the following questions:

- How much aggregates are consumed within a specific economic system during a given year?
- How much waste is generated?
- What is the social stock of aggregates?

Our model offers high-resolution results, covering all years from 1978 to 2050, for 31 provinces in mainland China, and 30 subcategories of sand and gravel end-use.

The model methodology is primarily based on the theory of material flow analysis and the social metabolism process of sand and gravel resources. It can be divided into three main parts:

1. Construction of the basic structure of the social metabolism of sand and gravel resources (Figure S3).
2. Estimation of the inflow, outflow, and social stock of sand and gravel resources in the stock stage (Figure S4).
3. Scenario analysis of future sand and gravel supply and demand (Figures S5-S7).

For detailed information, please refer to the updated Methods section in the main text. We hope the current model framework is now clearer.

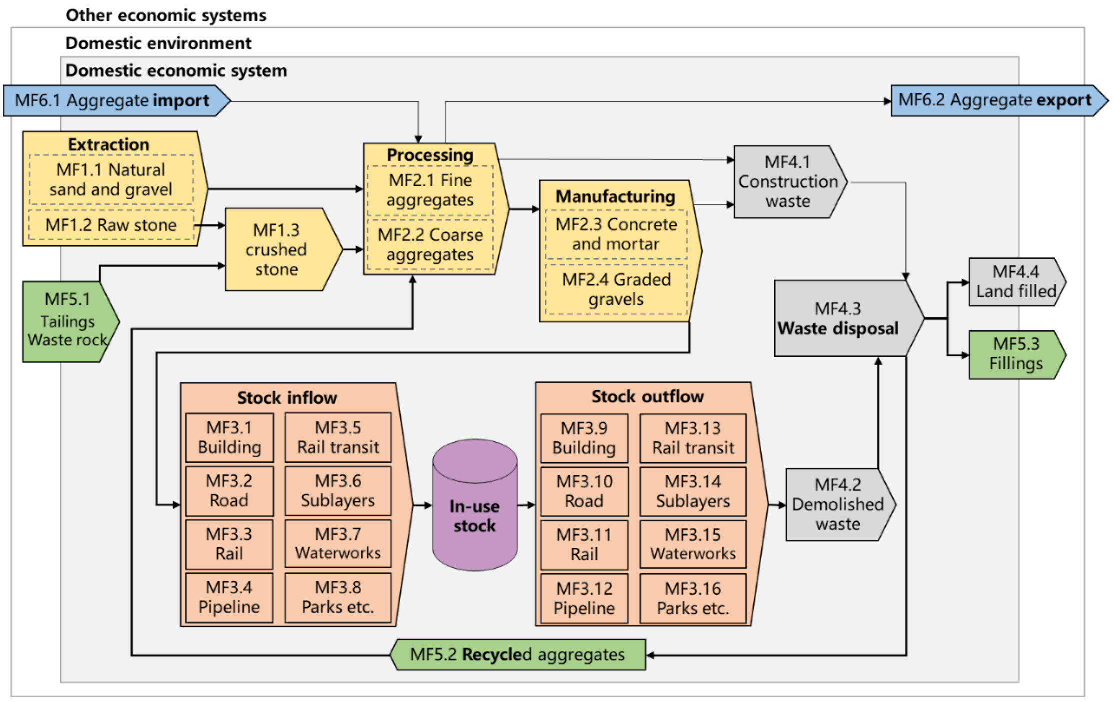

Figure S1 Aggregate metabolism model.

(2) A lot of energy has been spent to define the different types of aggregates (especially in SM), but the terms used in the manuscript are not always the best choice to be understandable to my point of view (e.g., “manufactured aggregates”).

Response:

Thank you for your comment. Through our research, we found that defining aggregates is crucial, as many related studies do not provide clear definitions (for instance, industrial sand used in chip manufacturing should not be included).

China has its standards and industry-specific characteristics for defining aggregates. As you mentioned, we indeed put considerable effort into this, engaging in discussions with experts from both industry and academia to rigorously define different aggregates, as well as to clarify the scope of this paper.

In response to your comment, we have reviewed the terminology used in the manuscript and made the following clarifications:

Natural aggregates: These include river sand, lake sand, desalinated sea sand, mountain sand, pit sand, and pebbles. They are naturally occurring rock particles extracted and screened by human labour or excavation equipment.

Manufactured aggregates: These consist of artificial sand and crushed stone, produced from raw rock, tailings, and waste rock through processes like soil removal, mechanical crushing, and screening.

We would like to note that the term “manufactured aggregates” may vary internationally. For example, it is sometimes referred to as:

- **machine-made aggregates** (https://www.sciencedirect.com/science/article/pii/S0950061820308333) or
- **artificial aggregates** (https://www.sciencedirect.com/science/article/pii/S0959652620352598).

We have adopted the term **manufactured aggregates** based on its usage in the Chinese national standards (http://c.gb688.cn/bzgk/gb/showGb?type=online&hcno=BFD788F1742125DC8E9922E38F6167BD), while also considering the terminology used in related international studies (https://link.springer.com/article/10.1617/s11527-011-9749-2).

Recycled aggregates: These are produced from construction and demolition waste and can substitute primary aggregates in various applications.

(3) Moreover, the title states that the study is about sand, while the article deals with all aggregates (including gravel, and crushed stone).

Response:

Thank you for your this point. While using "aggregates" in the title would indeed be more precise , we believe that "sand" is more accessible to a broader audience, which could encourage interest from experts outside the field.

Additionally, we have provided clear definitions and distinctions between sand and aggregates in the manuscript to support a more academic reading experience for our readers.

(4) The data used are a mix of literature-derived and expert insights, that would deserve being better referenced in some parts of the method, and it makes it hard to assess their quality.

Response:

Much of the underlying data in this study come from yearbooks and public databases, with a small portion obtained through expert consultations. The availability of sand and gravel data is quite limited. However, we have developed close relationships with the China Aggregates Association, and to the best of our knowledge, the sand and gravel data used in this study is currently the most detailed available for China.

We have reorganized the structure of the Methods section in the main text to provide a clearer and more coherent introduction to the CHAMPS model. Additionally, we have added Table S11 in the SI, which details the sources of the underlying data:

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

Category	Sub-Category	Underlying data in 2020		Material intensity in 2020 (t/unit underlying data)	Average lifetime (year)
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	
Waterworks		Concrete consumption for waterworks (kilo cubic meter)	347	1960	50
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
Railway	High-speed railway	Railway length (km)	431	120000	30
	General speed railway		1670	43000	30
Rail transit	Light rail	Rail transit length (km)	-	-	30
	Subway		754	70000	30

Pipeline	Tap pipe	Pipeline length (km)	42452	3300	30
	Sewer pipe		19344	3300	30
Rural house		Rural house area = Rural population * Per capita floor area (kilo square meter)	287746	1253	30
Park etc.		Park area (kilo square meter)	357000	1000	40

Note: See SI for detailed data sources.

(5) We found that the scenarios are also not extremely well supported (justification of the scenarios choice?), and one could argue that it is hard to assess the robustness of the results without at least sensitivity analyses on key parameters, such as lifetimes of products or recycling rates.

Response:

Thank you for your question regarding the scenario settings. The measures in the scenario analysis are primarily based on SSP scenarios and circular economy principles. These measures align the circular economy approach with the current state of the aggregates industry in China and were developed through consultations with industry practitioners, experts, and scholars. The specific measures and corresponding model parameters are detailed in Section 2 of Supplementary Notes and Figure S5-8.

We conducted an uncertainty analysis of all model parameters using Monte Carlo simulations, which demonstrated the strong robustness of the core model. The results are provided in the SI. Additionally, in the model, the calculated consumption of various types of recycled aggregates shows a linear relationship with the recycling rate, further supporting the robustness of the circular development aspect of the model itself.

(6) There are some figures of uncertainty analyses (a lot of them) in the SM, but no explanation of what they are, and how they were generated.

Response:

Thank you for the suggestion. We have added Section 1.5 in the SI notes to explain the uncertainty analysis.

S1.5 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.

In this study, we conducted an uncertainty analysis of the CHAMPS model and the results using Monte Carlo simulation. We anchored all model parameters and performed 1000 random samples within a ±10% range in normal distribution, with a confidence level of 99.5%. These 1000 sets of parameters were then applied to the CHAMPS model for repeated calculations, producing 1000 results.

Regarding the rationale for employing the normal distribution in Monte Carlo simulations, it is based on the assumption that the uncertainties of variables are symmetrically distributed around the mean. This suggests that deviations in both positive and negative directions 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 a common practice1.

As shown in Figures S28-S33, the results of the Monte Carlo simulations for Beijing are displayed. All 1000 results were plotted on the results graph. It is clear that the difference between the maximum and minimum data points for each year is quite small, generally within a 10% range. For major aggregate end uses such as housing and roads, only slight variations were observed and showed close agreement.

(7) In the end, the results fall a bit short, with bland recommendations such as promoting circular economy to reduce consumption of sensitive virgin resources.

Response:

Thank you for raising this. We have aimed to improve the specificity of the recommendations. Aside from reemphasizing the importance of the shift from natural sand to manufactured aggregates over the past decade, we highlight that China's construction stock is projected to reach saturation, making disposal of construction waste a higher priority, especially recycled aggregates. We have now been more specific about the solutions required for handling demolition waste and recycled aggregates:

Addressing the challenges of recycling construction and demolition waste (CDW) will require multiple policies in building new capacity and developing supply chains for recycled aggregates. Separating high-quality aggregates from mixed CDW is technically challenging so scaling the use of these aggregates will require advanced separation technologies to bring costs down, this would necessitate investment in research and development. A second challenge is market acceptance of these recycled aggregates, which would be improved through the *use of quality benchmarks along with clear technical standards. Boosting the market for recycled aggregates will likely require some mix of economic incentives (subsidy or tax reduction) for using recycled products, incorporating recycled materials in bid requirements, and promoting the standardization of reusable concrete components65. China's "green mine" policy promotes key strategies such as subsidies for intelligent operations, environmental protection, high-quality production, and effective management. It encourages large-scale ecological operations and the shift to a circular economy. Recognition programs and targeted incentives for innovators further support these goals66. Effective collaboration across technical, policy, and academic institutions will be needed to guide and monitor the development of a recycled aggregate market. If enough steps are taken the output of recycled aggregates can already meet most of the demand for aggregates at a recycling rate within a reasonable range in the future, according to our findings.*

Given the typical characteristics of sand and gravel as common-pool resources, both the transition from natural to manufactured aggregates and the need to develop a circular economy will require strong policy interventions. We conclude by stating:

The "large-scale but low-cost" nature of sand and gravel use has led to a sand crisis driving a depletion of a common pool resource, posing not only significant environmental risks but also serious social impacts. Illegal and excessive extraction has worsened the crisis, resulting in habitat destruction, biodiversity loss, and threatening long-term resource availability and ecological balance. China's success in transitioning from natural to manufactured aggregates (crushed stone) through strong policy guidance demonstrates the effectiveness of targeted regulations in mitigating these impacts. Furthermore, by integrating circular economy principles—such as promoting recycled aggregates and utilizing waste materials like tailings—further reductions in primary extraction and environmental degradation can be achieved. Looking ahead, recycling and managing CDW will require continued government support. Strong, evidence-based policy support and local supply-demand plans are essential for addressing sustainability challenges and providing valuable insights for rapidly growing economies.

(8) To be more specific on the "main" section of the article, the writing and argumentation about the importance of the research and its findings is a bit clumsy, with some approximations and common places, and little gaps in the logical flow of the text. We wish more rigor about facts and a clearer argumentation. The structure could be enhanced (for instance: avoiding talking about sand crisis, then local aggregate shortages, and final sand crisis again (p3)). The "main" part of the manuscript relies on an eclectic body of literature, while we would like to know more about similar attempts of quantification, methodologically speaking, and know more what other models did (see suggestions below).

Response:

Following your advice, we have revised the relevant sections as follows:

Aggregates (sand, gravel, and crushed stones) are essential for most modern construction. While materials like straw, wood, and clay can be used in specific cases, the heavy reliance on concrete-based construction has led to enormous demand for aggregates. At a global level, there is little risk of exhausting these resources, however, they are expensive to transport, and local escalating costs are expected to curb demand. As such, it's essential to conduct analyses at a local level1,6 to address specific challenges. In many regions, overexploitation has caused sand shortages and environmental damage7-10, especially from riverbed extraction, which harms both ecosystems and river channels9,11,12. This is often because towns built near rivers, where natural sand and gravel are ideal construction materials. In some areas, demand now exceeds the natural rate of replenishment13, leading to unsustainable extraction practices. Local shortages have driven up prices, fueling illegal extraction and exacerbating environmental and social impacts1. Sand and gravel issues are often overlooked – in part because they are so abundant – with the result of that this common pool resource is being degraded in several areas of the world14. Some have suggested that this trend has worsened to the point that we now face a sand (and gravel) crisis8,15-17.

(9) The manuscript (and SM) also lacks some references along the text. Example: "Using one cubic meter of concrete in China typically requires 1.8 tons of aggregates (l53-54), and other following figures: are they from the SN?

Response:

Thank you very much. These figures are based on some underlying results from our previous work (https://www.sciencedirect.com/science/article/pii/S0921344922000210), which form the foundation of this article. We have provided citations for this in the main text.

(10) Below are some specific suggestions, but we recommend the authors to work in depth on their study and manuscript, beyond these suggestions.

Response:

Thank you.

(11) Manuscript. Abstract:

• the method is not specified: "a scenario-based model that tracks flows and stocks" is quite unspecific.

• the concept of stock saturation may not be clear for readers

Response:

Thank you for your suggestion. We have made some adjustments to the abstract:

> *Aggregates (sand, gravel, crushed stone) make up half of all globally extracted materials and present significant environmental challenges. China, which consumes half of the world's aggregates, is undergoing profound shifts in both supply and demand, both now and in the future. Our scenario-based model tracks aggregate flows and stocks across 30 end-uses in Chinese provinces from 1978 to 2050. We find that China's aggregate demand peaked around 2015 along with a supply side shift from natural to manufactured aggregates. Total demand is projected to decline to ~50% of 2020 levels in circular economy scenarios. Per capita stocks are generally projected to reach saturation by 2040 with variations across provinces. Stock saturation may lead to increased availability of recycled aggregates, which could become a primary supply source. We highlight the critical need for stricter policies and regulations for the aggregate industry, offering insights for other economies facing similar challenges.*

(12) l32 : change for hyphen for dash

Response:

Thank you. Corrected.

(13) l37-38: "stabilizing at around half of 2020 levels under circular scenarios, with provincial per capita stocks approaching saturation around 2040": rephrase, unclear

Response:

Thank you. We changed it to:

> *We find that China's aggregate demand peaked around 2015 along with a supply side shift from natural to manufactured aggregates. Total demand is projected to decline to ~50% of 2020 levels in circular economy scenarios. Per capita stocks are generally projected to reach saturation by 2040 with variations across provinces.*

(14) l38-39: "We find a major shift from natural to manufactured aggregates": if it is "under circular scenarios" as written in the previous sentence, the contrary would have been quite surprising!

Response:

Thank you. We changed it to:

> *We find that China's aggregate demand peaked around 2015 along with a supply side shift from natural to manufactured aggregates. Total demand is projected to decline to ~50% of 2020 levels in circular economy scenarios.*

(15) L49 "(stone can be used once crushed)": this addition cuts the flow of reading and may be unnecessary to the demonstration.

Response:

Thank you, we removed this.

(16) L50: "Gt (billion tons)": full form and abbreviation in brackets is most common

Response:

Thank you, we corrected this.

(17) L60-61: "Often extracted from rivers, lakes, and mountains, sand and gravel are vital for construction but are often overexploited in certain regions, leading to a sand crisis": I am not sure to understand why we talk about sand and gravel's overexploitation, to finally talk about a sand crisis only (and not gravel, if it is also overexploited.

And why starting with "Often extracted from rivers, lakes, and mountains": does it help the argument? I personally wonder the link between where it is often extracted from, the sand crisis, and why we only talk about these three sources of aggregates when I read the sentence.

Response:

Thank you for these comments.

The term "sand crisis" is used here as a shorthand, but it refers to the overexploitation of both sand and gravel. As suggested, we have removed the "Often extracted from rivers, lakes, and mountains" sentence to make the text more concise. The revised text now reads as follows:

Aggregates (sand, gravel, and crushed stone) are essential for most modern construction. While materials like straw, wood, and clay can be used in specific cases, the heavy reliance on concrete-based construction has led to enormous demand for aggregates. At a global level, there is little risk of exhausting these resources, however, they are expensive to transport, and local escalating costs are expected to curb demand. As such, it's essential to conduct analyses at a local level1,6 to address specific challenges. In many regions, overexploitation has caused sand shortages and environmental damage7-10, especially from riverbed extraction, which harms both ecosystems and river channels9,11,12. This is often because towns built near rivers, where natural sand and gravel are ideal construction materials. In some areas, demand now exceeds the natural rate of replenishment13, leading to unsustainable extraction practices. Local shortages have driven up prices, fueling illegal extraction and exacerbating environmental *and social impacts1. Sand and gravel issues are often overlooked – in part because they are so abundant – with the result of that this common pool resource is being degraded in several areas of the world14. Some have suggested that this trend has worsened to the point that we now face a sand (and gravel) crisis8,15-17.*

(18) L60: "sand and gravel are vital for construction": in modern construction techniques yes, but construction is possible without sand and gravel I believe, with other natural materials (straw, wood, clay, etc.), so it may not be "vital". Rephrase.

Response:

Thank you for your suggestion. We have revised it to:

Aggregates (sand, gravel, and crushed stone) are essential for most modern construction. While materials like straw, wood, and clay can be used in specific cases, the heavy reliance on concrete-based construction has led to enormous demand for aggregates.

(19) L63: are we talking about "natural replenishment" on a biocentric aspect, or "aggregate supply", on a more technocentric aspect? I would have assumed that the natural replenishment of aggregates has been surpassed by aggregate demand as soon as concrete and asphalt concrete construction has been developed.

Response:

Thank you for this point. Here, we are referring to *natural replenishment*, based on the research (https://www.science.org/doi/10.1126/science.adj9593).

The formation of most rock takes hundreds of millions of years, making the process incredibly slow and incommensurate to the pace of our demand. However, the natural replenishment we are discussing here is not the slow process of rock formation, but rather the traditional process of natural aggregate replenishment. Rocks are eroded by river water, breaking down into sand and gravel, which are then transported downstream. According to China River Sediment Bulletin (http://xxzx.mwr.gov.cn/xxgk/gbjb/zghlnsgb/202407/t20240731_1759836.html), the annual sediment transport of major rivers in China is in the range of billions of tons, which, in earlier years, was sufficient to meet the country's demand for construction aggregates.

We have made some additions, and the updated text is as follows:

In some areas, demand now exceeds the natural rate of replenishment13, leading to unsustainable extraction practices. Local shortages have driven up prices, fueling illegal extraction and exacerbating environmental and social impacts1. Sand and gravel issues are often overlooked – in part because they are so abundant – with the result of that this common pool resource is being degraded in several areas of the world14. Some have suggested that this trend has worsened *to the point that we now face a sand (and gravel) crisis8,15-17.*

(20) L64-65: “particularly from waterbody extraction”: I believe there is a confusion between stock and flow: the stocks are being depleted everywhere because the creation flows are so slow. The stock is been depleted faster in waterbodies because it costs less to extract than from hard rocks.

Response:

Thank you. The "stock" in this paper refers to social stock (manufactured capital), not natural reserves, and "flow" pertains to material flows within the economic system, excluding natural regeneration. We have revised the relevant sections and removed the sentence.

(21) L65-67: “More sustainable alternatives, such as manufactured aggregates from rock quarrying and recycled aggregates from construction and demolition waste (CDW), offer solutions but require significant industrial inputs and careful ecological management.”: there are no references here, and first thing this sentence questions is: what is “more sustainable”? From which point of view? Which indicators? We can probably show that aggregates from waterbody are more sustainable on some indicators based on LCA: for instance, it consumes less energy to be produced, deteriorates machinery less, so globally the carbon footprint per ton is often smaller than those from hard rocks (see your ref #16).

Response:

Thank you. We have revised the sections and added references.

Regarding the term "more sustainable": sustainability here refers primarily to the ecological damage caused by extraction, particularly to aquatic ecosystems, rather than carbon emissions during production. Both manufactured and natural aggregates produce minimal emissions compared to cement production. For instance, according to Chinese government reports (Several Opinions on High-Quality Development of Aggregates Industry, https://www.gov.cn/zhengce/zhengceku/2019-11/13/content_5451478.htm), carbon emissions from the production of all manufactured aggregates would account for less than 0.5% of China's total emissions.

In terms of sustainability, manufactured aggregates are generally considered more ecologically responsible. The UNEP report (Sand and Sustainability, https://www.unep.org/resources/report/sand-and-sustainability-10-strategic-recommendations-avert-crisis) and China’s green mine policies (https://www.gov.cn/zhengce/zhengceku/202404/content_6945747.htm) support this. The primary environmental concern remains the damage from natural aggregate extraction, as highlighted in multiple reports (UNEP, China Aggregates Association: https://www.aggbusiness.com/feature/chinas-green-quarrying-revolution; http://en.zgss.org.cn/industry/d_6232e1ef8e483f00933e91e1.html). Now the sentences read:

> *Supply-side changes are important and less environmentally impactful resources include crushed rocks from quarries (crushed stones or manufactured aggregates; see the definition in the Methods section), secondary aggregates from construction and demolition waste (CDW) and ore-sand (a by-product of mineral processing). However, blasting and crushing of rocks or using ore-sand still has environmental impacts18,19, requiring strict management measures, which are more feasible to regulate than widespread illegal extraction of nature sand and gravel.*

(21) L65: "manufactured aggregates from rock quarrying": are you talking about natural aggregates produced from crushed rocks from quarries, or by-products of other manufacturing industries? Unclear. Please specify in the different places where you use manufactured aggregates, as I am not sure it is a dedicated term (e.g., l337). Crushed stones/ aggregates is probably a clearer term.

Response:

Thank you for your suggestion. We have made some revisions here to improve clarity:

> *Supply-side changes are important and less environmentally impactful resources include crushed rocks from quarries (crushed stones or manufactured aggregates; see the definition in the Methods section), secondary aggregates from construction and demolition waste (CDW) and ore-sand (a by-product of mineral processing). However, blasting and crushing of rocks or using ore-sand still has environmental impacts18,19, requiring strict management measures, which are more feasible to regulate than widespread illegal extraction of nature sand and gravel.*

Indeed, the UNEP report (https://unepgrid.ch/storage/app/media/Publications/3.%20FINAL_GSOI-GSA-2022-002_What%20is%20sand.pdf) states that there is currently no universally accepted definition of aggregates. UNEP specifically published this report to address the issue, and the conclusion remains unclear. This is why we dedicated substantial space in both the article and SI to introduce our definition of aggregates, which combines international terminology with Chinese characteristics. "Manufactured aggregates" is the term commonly used in both industry and academia, and it can also be referred to as "crushed stone."

(22) L68-69: "Life Cycle Assessment (LCA) has identified distinct environmental impacts of both traditional and alternative aggregates": I do not understand this sentence. LCA proposes to quantify specific environmental impacts, this impact being somewhere between 0 and infinity. What is an impact then? Plus, the studies you are citing are not the most recent studies or reviews on aggregate LCAs. For instance, Braga et al. 2017 used derived models

Response:

Thank you, we have removed this sentence. What we intended to convey was that some LCA studies have examined the environmental impacts of producing manufactured sand from traditional natural sand and crushed stone.

(23) L82: “paving road sublayers”: I do not know if it is advised to use common language only. Maybe you would like to specify which layers, according to pavement design vocabulary. Here I believe you are talking about subbase courses. By using non-specific language only, you are understandable by non-experts in infrastructure, what is good, but it gives a sense of lack of knowledge in infrastructure when experts read such a sentence.

Response:

Thank you, we have corrected following your suggestions.

(24) L82-83: “rather than in higher-grade uses like structural components requiring high-quality concrete”: I believe you are first talking about asphalt concrete (made of 95% of aggregates, that represent most of the roads in the world), then maybe concrete (representing a small part of the pavements, but you will not have low quality concrete for roads anyway).

Response:

Thank you for your comment. There is a slight misunderstanding.

In this context, we are specifically referring to structural components in buildings, such as load-bearing structures. These components require high-quality concrete, which, in turn, demands high-quality aggregates. Therefore, the quality standards for aggregates in these applications are notably higher.

Now the sentences read:

> *Even in high-income countries with more economic resources, the use of recycled aggregates is predominantly confined to construction projects that do not require high-grade materials such as paving road subbase courses, rather than in higher-grade uses like structural components requiring high-quality concrete26.*

(25) L83-84: “Sustainable management of these resources is a complex task hindered by a lack of comprehensive data”: please be specific about what you mean, it could be read as a common place with lack of substance.

Response:

Thank you for your suggestion. We have revised the text as follows:

Sustainable management of these resources is complicated by a lack of reliable monitoring data on extraction and usage hinders the formulation of effective policies28. This is especially challenging for developing countries29, which are the primary drivers of aggregate demand during periods of rapid development. In these regions, high demand is often accompanied by unregulated extraction practices where robust management policies are lacking.

(26) L85: “Obtaining timely statistics for aggregates is challenging”: statistics about what? Please specify.

Response:

Thank you. We have revised the text along with our response to #25.

(27) L94-95: “structural changes in greenhouse gas emissions”: about resource? Aggregates? I do not see the link here with the surrounding text.

Response:

Thank you for this point. We have referenced the article "Structural decline in China’s CO2 emissions through transitions in industry and energy systems (https://www.nature.com/articles/s41561-018-0161-1)" They mention, "*We conclude that the decline of Chinese emissions is structural and is likely to be sustained if the nascent industrial and energy system transitions continue*." However, subsequent research has found that this decline in emissions may be temporary, though China's structural transformation is indeed taking place. We have revised the text to read:

Studies indicate a potential peak and subsequent decline in China's resource consumption around 202022 and structural changes in China’s greenhouse gas emissions38.

(28) L101: “Research on the future demand and supply of aggregates in China is scarce”: but you are addressing the period 1978-2050. So maybe adapt the sentence to justify why you also considered past years.

Response:

Thank you. This sentence is meant to emphasize the importance of future research, with historical data being a crucial foundation for scenario-based studies of the future. Therefore, we first need to establish data from 1978 to the present before we can effectively research future developments.

(29) L110: “foster sustainability”: again, I think it would be clearer if you define what

you mean by sustainability in your specific study.

Response:

Thank you. We have rephrased the text as follows:

Here we introduce the China Aggregate Metabolism Provincial Scenarios (CHAMPS, Figure S3-5) model. CHAMPS enables a comprehensive understanding of the historical, current, and future dynamics of aggregate supply and usage across mainland China and its 31 provinces (see Figure S2) between 1978 and 2050. It is a dynamic model that tracks the flows and stocks of materials across their entire lifecycle and various uses. We include 30 distinct end uses which are divided into eight categories. We project trends to 2050 under six main scenarios and explore how circular economy approaches can be effectively applied in the aggregate industry.

(30) L115: "that incorporate the circular economy's core principles of Reduce, Reuse, Recycle": please add a reference.

Response:

Thank you. We have added the reference:

https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits

(31) L101-116: the objective of the research is not clearly expressed.

Response:

Thank you. We have revised this section to emphasize the research objectives of the paper:

Research on China's future aggregate demand and supply is limited, despite the country accounting for half of the global aggregate extraction6. There is also a significant gap in assessing its recycling potential4,22. Given the localized mining and use of aggregates37, detailed analysis at sub-national levels is vital. To address these gaps, we aim to understand the dynamics of aggregate demand and supply. We analyze historical, current, and future material stocks and flows, evaluate the potential of circular economy strategies, and understand policy development for China's large-scale aggregate industry and its implications for other developing countries.

(32) Table 1:

• the source of examples are unclear: is it from ref #36, or explained in SN? Is the time horizon always 2050 (example #1)? If yes, specify in the title of the column, or in each suitable example (e.g; "it will drop from a baseline of 50.2 m² to 40.1 m²." misses a time horizon).

Response:

Thank you very much. These sources have all been referenced in the SI, and we have also added Table 1 as per your suggestion. We rephased the "example" as "An illustration of this scenario in 2050" in Table 1.

(33) "Lifetime Extension": is it a credible scenario, considering the impact of climate change on infrastructure and buildings, under SSP2?

Response:

Thank you for your suggestion. This issue is relatively unique to China. Due to rapid development, the average lifespan of buildings in China is relatively short, typically less than 35 years, whereas in developed Western countries, building lifespans can range from 80 to 100 years. Therefore, in the context of sustainable development, extending the lifespan of buildings in China will be crucial in the future. In this study, we have referenced literature (https://www.nature.com/articles/s41560-019-0512-1) to establish parameters for the lifetime extension scenario, as detailed below and included in the SI.

[Figure Redacted]

Source: China National Statistics and https://www.nature.com/articles/s41560-019-0512-1

We have also noted this in the SI:

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.*

(34) In general in scenarios: did you incorporate impact transfers / feedback loops between material quality changes brought by including more recycling byproducts,/ using lightweight design and consumption changes? Example: to reduce the material intensity of final uses, I need to substitute aggregates by other materials, what will transfer environmental impacts on other commodities.

Response:

Thank you for your question. Aggregates are indeed among the least expensive materials, but due to their large quantities and structural importance, finding suitable substitutes is challenging. As a result, the environmental impact of alternative materials is not a primary concern here. Instead, reducing the strength coefficient can be addressed through improvements in building structures, such as optimizing design to use less concrete per square meter, or employing hollow concrete blocks, which help reduce aggregate consumption.

(35) L124-126: "This decrease is attributed (…) as well as potential demographic change": we do not know if there is a demographic change, and the attribution to demographic change is a possibility but unclear?

Response:

Thank you for your comments. Following the reform and opening-up, China experienced rapid population growth. However, due to national policies on planned population control, changes in social population structure, and evolving family values, China's population has now begun to decline.

The demand for buildings is determined by both per capita building demand and population size. When per capita building demand remains constant, population size plays a significant role in influencing building demand, which in turn impacts the demand for sand and gravel.

In our specific model, within the demand-side portion of the scenario model, the construction demand layer incorporates metrics like stock density, including per capita living space, which is then multiplied by population size (as shown in Figure S6). The population data we use is based on the SSP2 scenario.

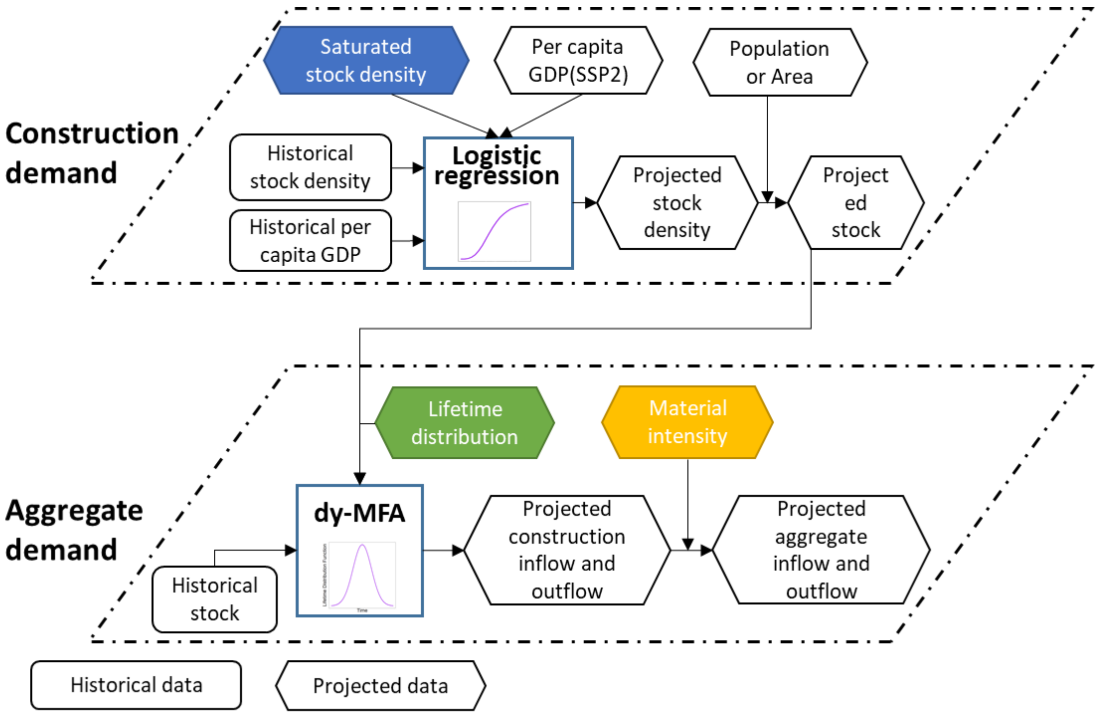

Figure S6 Scenario analysis model on the demand side.

(36) L125: "the saturation of the construction industry": I do not understand what it means.

Response:

Thank you. We have rephrased this sentence and added a reference (https://www.scmp.com/economy/china-economy/article/3152916/chinas-property-and-construction-sectors-contract-third) to make the meaning clearer:

> *This decrease is attributed to factors such as the slowdown in China's construction industry42 and the socioeconomic impacts of the COVID-19 pandemic, as well as demographic change43.*

(37) L131-132: "Significant demand declines are anticipated for both buildings and infrastructure; by 2050, under the All Measures (AM) scenario": please remove semi-colon

Response:

Thank you and corrected.

(38) Figure 2: the choice of the scale in the legend is questionable (7, 1 or 0.3 Gt: why these choices?)

Response:

Thank you very much. The scale was automatically generated by the plotting package. To improve readability, we have annotated the specific flow values directly on the diagram.

(39) L248: "exceeded 23 t/cap": per year, on on the period 2016-2020?

Response:

Thank you. We have added "in 2020."

(40) L257: "they ranged from 147.4 to 360.1 t/cap": you had 2 significative digits, rounding the result to the tonne on L248, now you have 4, rounding the result to the decimal… Pick a number and stay consistent when given your results.

Response:

Thank you. In the text, we have retained one decimal place for absolute values and kept percentages as whole numbers. Regarding the section on L248, it refers to a specific range, so we kept it as an integer.

(41) L374-381: "The primary challenges of the sand and gravel crisis encompass environmental impacts related to water bodies, effects on biodiversity, and socioeconomic issues. (…) developing countries need to engage in scientific evidence-based modeling to evaluate these factors. (…) conducting a material flow analysis is foundational to this scientific evidence-based modeling":

you need to close the loop of your argument (and this is a general comment for the article). Why is MFA foundational? Because it can allow to calculate the different sustainability metrics at the regional scale based on the different resources produced/consumed, depending if we have a production or consumption-based approach. Example; you have the LCA results of different types of aggregate productions, you know the amount that I produced/consumed => you can calculate the total environmental impacts, and evaluate mitigation strategies. You need to explicit that (more synthetically than here, but your readers will not read your mind).

Response:

Thank you very much. Based on your suggestion, we have made revisions. The updated version of this paragraph now reads as follows:

We emphasize that the sand crisis is not a simple global issue, but rather a local one, making regional and local studies essential. The crisis is driven by sudden imbalances between demand and natural resource availability. However, it's important to recognize that how this crisis is framed can oversimplify the complex *political, social, and environmental dynamics at play, potentially leaving out important perspectives and solutions17. The direct and primary challenges of the sand and gravel crisis include environmental impacts on water bodies, effects on biodiversity, and socioeconomic issues stemming from mining activities, including illegal extraction20,70. Consequently, policymakers, particularly from developing countries, need to engage in scientific evidence-based modelling to evaluate these factors. Conducting a material flow analysis is foundational to this process as it enhances the understanding of resource stocks, flows, and extraction-processing-use landscapes at the regional scale. Integrating MFA with life cycle assessment results allows for a more comprehensive assessment of these impacts and the identification of potential mitigation strategies. This approach enables a more comprehensive evaluation of sustainability challenges and opportunities in the aggregate industry which includes both a supply- and demand-side perspective.*

(42) L391-393: "we conclude that robust, evidence-based policies and regulations are essential to ensure sustainable management and prevent overexploitation and a sand crisis.": don't you think it is a bit of a common place? ". This sentence is equally true, I believe: "we conclude that robust, evidence-based policies and regulations are essential to ensure sustainable management and prevent (whatever is negative from a sustainable point of view)". You can make a better, more specific conclusion of your discussion section, based on your analysis.

Response:

Thank you for your suggestion. We have made some revisions, and the section now reads:

The "large-scale but low-cost" nature of sand and gravel use has led to a sand crisis driving a depletion of a common pool resource, posing not only significant environmental risks but also serious social impacts. Illegal and excessive extraction has worsened the crisis, resulting in habitat destruction, biodiversity loss, and threatening long-term resource availability and ecological balance. China's success in transitioning from natural to manufactured aggregates (crushed stone) through strong policy guidance demonstrates the effectiveness of targeted regulations in mitigating these impacts. Furthermore, by integrating circular economy principles—such as promoting recycled aggregates and utilizing waste materials like tailings—further reductions in primary extraction and environmental degradation can be achieved. Looking ahead, recycling and managing CDW will require continued government support. Strong, evidence-based policy support and local supply-demand plans are essential for addressing sustainability challenges and providing valuable insights for rapidly growing economies.

(43) L396_397: "We referred to China's standards60,61 and international reports62 to define the aggregate resource in our model": okay, but be sure the vocabulary is not specific to China's standards, and easily understandable by non-Chinese readers".

Response:

Thank you for. We have carefully reviewed the terminology used in our model.

We categorize aggregates into three main types: Natural aggregates, Manufactured aggregates, and Recycled aggregates. We have provided detailed explanations for these categories in response to previous questions. This classification is widely recognized and commonly used in both literature and reports globally. For example, terms such as Natural aggregates (https://www.sciencedirect.com/science/article/pii/S1877042813020788), Manufactured aggregates (https://link.springer.com/article/10.1617/s11527-011-9749-2), and Recycled aggregates (https://www.sciencedirect.com/science/article/pii/S0950061818307451) frequently appear in relevant publications.

Additionally, we have restructured the definition section in the main text to enhance clarity, and further details are provided in Figure S1 and the SI for your reference.

(44) L488-494: "This curve is derived through logistic regression analysis and connected to future per capita GDP to estimate future per capita stock.": you wrote earlier that there was a decoupling between aggregate consumption and GDP (l269-274): isn't it contradictory?

Response:

Thank you for your question. The distinction lies between stock and consumption, and they are not contradictory.

- The consumption (flow) of sand and gravel has decoupled from GDP, while consumption represents the incremental increase in stock.
- Per capita stock is closely related to economic development (GDP), as the stock of sand and gravel provides essential services to society and is directly linked to the economy.

The decoupling of GDP and consumption reflects the transformation of resource use as society develops. Conducting scenario analysis based on the relationship between per capita stock and economic development is a common practice in industrial ecology research.

(45) L496-498: "Lifetime distributions for these uses were devised based on local standards and insights from developed economies..": we can expect lifetimes to be a key parameter of your results. Can you specify more (or tell me where you mentioned) the lifetimes you used? I found some past lifetimes in the excel spreasheet, that seem relatively short (maybe due to regional differences between China and the rest of the world), and I did not see the distribution parameters selected, neither the specific sources of the lifetime consideration, or prospective lifetimes in the different scenarios

(do they only change in the lifetime extention scenarios?). Especially, what is derived from standards, and from "insight from developed economies", and what are these insights?

Response:

Thank you for this important question. The lifetimes of residential buildings in our study are primarily derived from literature sources, while the lifetimes of roads and other infrastructure are based on China's national standards. We have provided detailed references in the SI.

Regarding the distribution, Miatto et al. (https://www.sciencedirect.com/science/article/pii/S0921344917300265) discussed that a log-normal distribution, and more generally, right-skewed distributions, are well-suited for short-lived buildings, which are typical in China. We have followed this approach, as well as the previous study by Yu et al. (https://www.sciencedirect.com/science/article/pii/S0921344919305737), which applied a log-normal distribution for the lifetime of buildings and infrastructure in China. In our model, the standard deviation for all final uses is set at 30% of the expected lifetime.

Additionally, lifetime extensions are only applied in the scenarios where we explicitly model the effects of extending building and infrastructure lifespans. Further details on the parameters and data sources used for the lifetime considerations can also be found in the SI.

(46) Supplementary material

General comments:

• an illustration of your method would be welcome, as well as a table with your variable names, as they are very numerous (MF X.Y, lambas, sigmas, etc.).

• A synthesis of how the model works in general would also be more than welcome. I personally had a hard time trying to understand your methodology, and I still do not have a clear idea of what has been done.

• I also believe you did not explain all your variables (e.g., mu, sigma): please double-check.

Response:

Thank you very much. We have added the information to the Supplementary Information (SI).

(47) Please place the figures as close as possible from the text where you discuss them, it eases the reading

Response:

Thank you for your suggestion. We would also like to present the figures this way but journal submission requirements need the current, seprate layout.

(48) L262: “"China Resource Comprehensive Utilization Annual Report" and expert consultations”: these sources are important to assess how credible are “the utilization rates of aggregate waste from concrete parts of residential construction, waterworks, and processing waste”: please provide the specific references.

Response:

Thank you for pointing this out. We have referenced the China Resource Comprehensive Utilization Annual Report (in Chinese, available at https://www.gov.cn/gzdt/2013-04/08/content_2372577.htm and https://www.ndrc.gov.cn/fzggw/jgsj/hzs/sjdt/201410/t20141015_1130457.html). Below is the translation of the relevant content:

"In 2011, the comprehensive utilization of tailings amounted to 269 million tons, reflecting a year-on-year increase of 23.1%, with a utilization rate of 17%, an improvement of 1.3 percentage points compared to the previous year. Of this total, the recovery of valuable components from tailings accounted for approximately 3%, with a resource recovery volume of 8 million tons. The production of building materials made up about 43% of the total tailings utilization, while filling of mined-out areas accounted for about 53%. The annual output value of comprehensive tailings utilization reached 46.8 billion yuan."

(49) Section 1.1.2: some elements would be interesting to set the table in the “main” section of the article (ref 6-8) about previous research, and their methods.

Response:

Thank you very much. Due to space limitations, we have included the methodological discussion related to aggregate research in the Supplementary Information. Please refer to Figure S12-13 and Supplemental Notes 3.8.

(50) L595-598: “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.”: I do not understand this part of the model, what do you mean by “as identified in the demand-side”?

Response:

Thank you very much for your question. Allow us to clarify.

The original text explains how recycled aggregates are calculated. Specifically, recycled aggregates are determined by multiplying the amount of waste generated by the recycling rate we set. Waste generation primarily originates from the outflows, which are derived from the demand-side model's outflow data. The phrase "as identified in the demand-side" refers to the explanation of outflows within the demand-side model, rather than the demand side alone. Since recycled aggregates are sourced from waste generation, and waste generation is based on demand-side scenario analysis, this connection is crucial. While recycled aggregates are considered one of the sources of aggregates, they are ultimately categorized as part of the supply side.

(51) L625: "as detailed in Chapter 3": I do not see any reference, which chapter 3 are you talking about?

Response:

Thank you and corrected the typo.

(52) Reviewer #2 (Remarks on code availability): We did not see any code, notebook, or accessible calculation, but we had a look at the excel spreadsheet with the key parameters values. The values are clearly reported, but not standalone. Lifetime expectations seem quite short.

Response:

Thank you. In the initial submission, we have uploaded the code.

The lifespan distribution section is listed separately in the Excel dataset. Additionally, we have included Table S11 in the SI, which lists the expected service life of various end uses for different time periods, using Beijing as an example (previously referenced in Response #4 with Table S11).

Response to Reviewer #3:

(1) The manuscript models various scenarios for the future stocks and flows of aggregates in China. Given China's role as a major consumer and producer of aggregates, this study holds global significance. It is striking to see the evolution of China's aggregate supply and demand, as it reflects an increasing substitution of natural aggregates with crushed stone, with the model's "All Measures" scenario indicating a potentially significant contribution from recycled aggregates in future supply. There is increased awareness of the urgent need to address the global sand sustainability crisis, and China has demonstrated commitment to this objective, as reported by the authors' work.

A recent comprehensive study by The University of Queensland and the University of Geneva [1] has identified China as the largest market for ore-sand, a purpose-made aggregate generated as a co-product or by-product of mineral ores. Vale's Brucutu mine has been the first successful case of ore-sand production at an industrial scale in Brazil. Researchers proved that Vale's sand has a lower environmental footprint when compared to traditional sand sources such as river sand or manufactured sand [1]. Furthermore, a 2022 report by the United Nations Environment Programme (UNEP), cited by this work's authors [2], has introduced ore-sand as an alternative source of aggregates at scale and, therefore, a promising solution to the global sand sustainability and mine tailings crises.

Depending on the ore body characteristics and technologies employed, ore-sand may have potential advantages compared with sand sourced from recycled materials (e.g. from construction and demolition waste), such as better control over product quality (e.g., the avoidance of contaminants in the product), enhanced workability, strength, and durability, lower production costs (due to fewer comminution infrastructure requirements and savings in mine waste management), and possibly greater consumer acceptance of an engineered material versus recycled waste. These and other potential benefits could position ore-sand as a crucial future resource for sustainable construction in China.

Response:

Thank you very much for these comments.

In China, ore aggregates refer to tailings, which are included in the definition of aggregates in our SI. The definition states that tailings are one of the sources for manufactured aggregates. This definition in our SI is referred from the Ministry of Industry and Information Technology and other ten departments' guidance on the high-quality development of manufactured aggregates, which mentions tailings as a source of manufactured aggregates.

In our work, ore aggregates are indeed included as part of the manufactured aggregates. In our previous article (https://www.sciencedirect.com/science/article/pii/S0921344922000210), which is the basis of this work, we specifically marked tailings as a source in the Sankey diagram. However, the proportion of sand and gravel produced from tailings is relatively small in China, accounting for less than 3% of the supply side, which is why we didn't specifically emphasize them in the article.

As for the situation of tailings in China's aggregate industry and why their share is small, based on our previous industry research and consultation with stakeholders, we found that many reports from the Solid Waste Division of the China Sand and Gravel Association focused on tailings. However, since tailings often contain valuable metal elements or other high-value materials, and current circular economy initiatives in the industry mean there is a focus on extracting these materials. The process involves crushing the tailings into fine powder and using processes like hydrometallurgy for further extraction and refining, which is fundamentally a different market from aggregates.

We consulted experts from the China Sand and Gravel Association about the current situation and the potential of using tailings for sand and gravel production. They indicated that using tailings for aggregates poses several challenges. First, tailings may contain harmful substances that could negatively affect concrete production (such as heavy metals or acidic/alkaline compounds that impact concrete quality). Second, the density of ore-based sand is often higher than standard aggregates, which could increase the risk of foundation subsidence if used extensively in construction. Additionally, there is a potential risk of radioactive elements in ore sand. For these reasons, the use of ore-based sand is not prioritized within China's current aggregate market framework.

Regarding the 2022 report from the University of Geneva, which mentioned China as a significant producer of ore-sand, the original text reads as follows:

> *"The current list of potential major producers of ore-sand with local proximity to markets is dominated by China, but also includes India, Mexico, Indonesia, South Africa, the Philippines, Turkey, USA, and Chile."*

We understand this statement to mean that China has the potential to utilize ore-sand on a large scale, rather than implying that it is currently being used extensively. Based on the 2014 National Development and Reform Commission (NDRC) report on the comprehensive utilization of tailings, the volume of tailings used was estimated to be less than 100 million tons. This contrasts with the demand of around 20 billion tons in 2020 and approximately 10 billion tons projected for 2030.

Therefore, while ore aggregates (tailings) are included in our model we did not emphasize them and we do not think they will play a significant role in the construction industry. Based on your suggestion, we have now added further discussion on this topic in the discussion section:

> *Additionally, ore-sand (from tailings and waste rock) is considered part of the broader category of manufactured aggregates67.However, the share of ore-sand in aggregate production in China remains relatively low (less than 2%). This is primarily due to concerns over potential pollution risks, excessive density, and recommendations to prioritize tailings for extracting valuable metals instead. It is reported that the stockpile of tailings and waste rock in China has reached 60 billion tons68, which may become an alternative source of natural aggregates in the future. However, detailed statistics and research on tailings ponds are severely lacking69, and whether or how to use these materials still requires further investigation (see Supplemental Notes 3.9 for extended discussion).*

(2) In their current study, the authors have chosen not to address ore-sand as a future resource option. Instead, they explore other circular economy strategies, such as reducing the extraction and production of aggregates through enhanced use of the built environment. This includes optimising material intensity, extending the lifespan of buildings and infrastructure, increasing the recyclability of construction and demolition waste (CDW), and combining these measures. While these strategies are valuable and complementary, omitting ore-sand as a potential solution seems to be a significant oversight. The authors have adopted a broader definition for manufactured sand, which appears to consider fine aggregates repurposed from tailings and waste rock; this is, however, distinct from ore-sand [1]. I recommend that the authors expand their conception of the circular economy by incorporating an analysis of ore-sand as a viable alternative for sustainable sand sourcing in China and other regions (e.g. through exports). This inclusion would provide a more comprehensive understanding of circular economy transition possibilities in China, as the manuscript title claims.

Response:

Thank you very much for your thoughtful question.

We have described our reasoning for not focusing on ore-sand above. But just to clarify how it is included in our model, both in terms of model structure and data. Ore-sand can be summarized as tailings and waste rock associated with mining activities. Waste rock refers to the overburden removed during metal mining, and tailings are low-metal-content materials with no high-value use. Since these two are quite similar, they should be unified under the term ore-sand.

Thus, ore-sand can be categorized into two types:

- Immediately usable materials: These are directly used to produce manufactured aggregates, and can be considered equivalent to primary aggregates. This distinction is supported by policy documents (https://www.gov.cn/xinwen/2019-11/16/content_5452658.htm). However, the policy's emphasis on "conserving natural resources" suggests that tailings and waste rock, though used for manufactured aggregates, still differ from primary stone aggregates. They are viewed more as part of waste reutilization efforts.

- Stockpiled tailings: This category consists of waste that already poses environmental risks. It can be broadly defined as a secondary resource and serve as a substitute for manufactured aggregates, but it is not classified as recycled aggregate because it has not previously entered the economic system.

According to documents from China's central decision-making body (NDRC), China generates approximately 1.5 billion tons of tailings annually, with a comprehensive utilization rate of around 20%. Of the utilized portion, half is used for building materials, and the other half for mine backfilling, with only 3% used for metal extraction. This means that around 100-200 million tons of tailings replace primary stone in building material production each year. Although the absolute volume is significant, it represents only about 1% of China's aggregate consumption, making its relative impact small. For this reason, we did not discuss it separately in our current model.

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

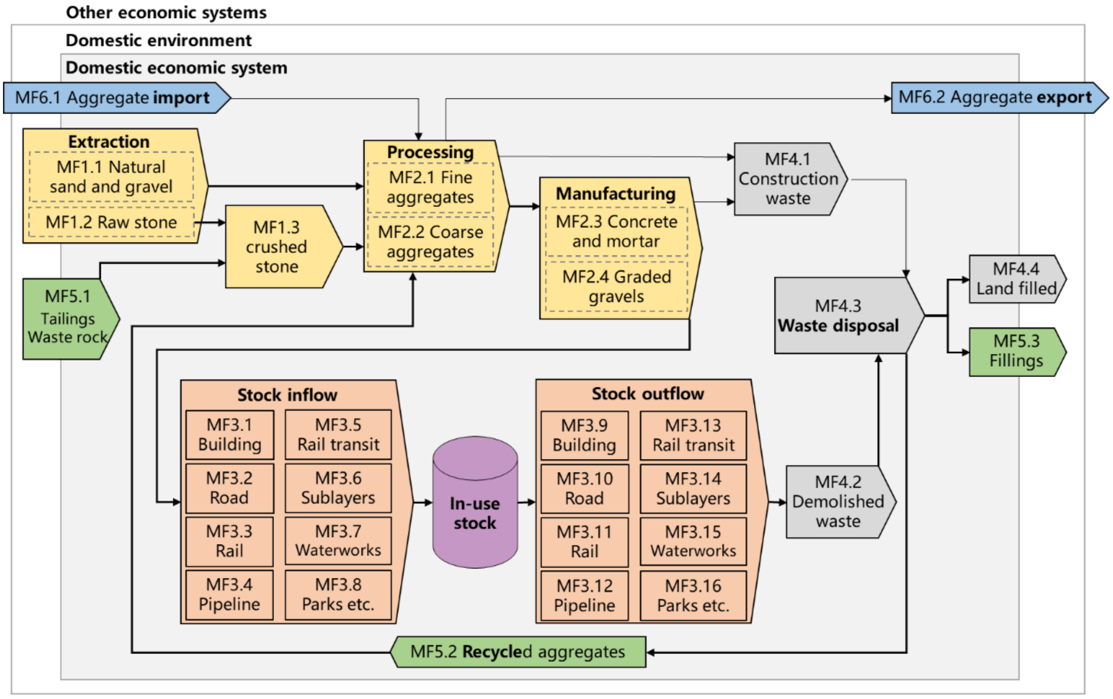

Figure S3 Aggregate metabolism model.

Thank you for encouraging us to explore this topic further. We have included this extended discussion in Supplemental Notes 3.9.

(3) Additionally, the manuscript's reference to "circular development" as a scenario focused on recycling should be revised. Recycling is traditionally positioned near the bottom of the waste management hierarchy, representing an end-of-pipe solution within a linear system. In contrast, by incorporating innovation and circular economy principles from the design perspective (i.e., designing out waste rather than designing with waste [3]), as in ore-sand co-production or by-production, it is possible to substantially increase the efficiency of using mineral (and other) resources and, therefore, significantly reduce the impacts associated with mine waste and the supply of aggregates from conventional sources (e.g. from rivers or quarries). In this sense, I recommend that the authors reframe the "Circular Development" scenario as "Improved CDW Recycling" or a similar term to accurately reflect the strategy's nature within the waste management solutions hierarchy.

Response:

Thank you and we changed the scenario name to “Improved Recycling” following your suggestions.

(4) In conclusion, this manuscript could benefit from a broader perspective on

sustainable aggregate sources, particularly by integrating ore-sand into its analysis. By considering this gap more carefully, the authors can present a more robust and forward-thinking evaluation of circular economy strategies in China's aggregate context.

References

[1] Golev, Artem, Gallagher, Louise, Vander Velpen, Arnaud, Lynggaard, Josefine R., Friot, Damien, Stringer, Martin, Chuah, Stephanie, Arbelaez-Ruiz, Diana, Mazzinghy, Douglas, Moura, Luanna, Peduzzi, Pascal, and Franks, Daniel, M. (2022). Ore-sand: A potential new solution to the mine tailings and global sand sustainability crises: Final report. Brisbane, Australia; Geneva, Switzerland: The University of Queensland; The University of Geneva. https://doi.org/10.14264/503a3fd

[2] UNEP 2022. Sand and sustainability: 10 strategic recommendations to avert a crisis. GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland. https://www.unep.org/resources/report/sand-and-sustainability-10-strategic-recommendations-avert-crisis

[3] https://www.ellenmacarthurfoundation.org/topics/circular-design/overview

Response:

Thank you very much for highlighting the ore-sand aspect of the model and for the citations.

As mentioned in our earlier responses, ore-sand is indeed included in our model. However, the direct use of tailings as aggregates in China remains very limited. Due to a lack of data, we are unable to isolate and specifically discuss the contribution of tailings and waste rock to manufactured aggregates in our model, but given its small contribution, other competing demands for the ore-sand (including metal recovery), and quality concerns it is likely to play little future role.

Current Chinese policies prioritize the further refining of tailings for extracting (rare) metals, rather than their use in construction materials. Based on discussions with industry experts, tailings are not viewed as a major focus for future development in aggregate production. With the increasing importance of recycling flows, construction and demolition waste may represent a more significant area of interest. Additionally, the physical characteristics of tailings and waste rock do not always make them suitable for use as construction aggregates. For instance, some tailings are ground into fine powder during hydrometallurgical processes, rendering them unusable as aggregates, while others have densities that could cause structural issues such as building subsidence.

In future scenarios, China's aggregate demand is projected to decrease significantly, and even if manufactured aggregates come entirely from primary stone, extraction levels should remain acceptable. However, we stress the importance of utilizing tailings and waste rock where feasible to reduce reliance on primary stone.

Once again, we thank you for this insightful suggestion, which has prompted us to take a deeper look into this issue. We included this extended discussion in the SI.

Response to Reviewer #4:

The paper is generally good and presents new understanding of recycled aggregate life cycles in China. I appreciate and comment the authors' hard work but suggest some improvements are required. I have four main comments and provide line-specific comments thereafter.

Response:

Thank you for the positive comments and insightful suggestions. These have helped improve the manuscript. We have carefully addressed all the points raised and made the necessary revisions as described below.

(1) The supplementary information is substantial and proper understanding and scrutiny is difficult with the manuscript alone. Furthermore, some information within the supplementary information cannot be properly studied in their current format. Figures S28-S33 (the results of the uncertainty analysis) are too small to read.

Response:

Thank you for the suggestion. We understand that the volume of information may make reading a bit challenging. As per the journal's requirements, the text, figures, and tables are presented in separate sections. To improve readability, we have reorganized the SI and made sure to reference the corresponding supplementary figures and tables within the main text.

Additionally, following your advice, we have increased the font size for certain figures, particularly S28-33.

(2) The authors discuss assumptions related to aggregate stocks and flows in the modelled scenarios, but justification of the dynamic MFA model parameters appear to be lacking.

2a) Log-normal distributions are assumed – a choice which, though common practice, is not explained, and alternatives are not discussed. Related to this is the uncertainty analysis. Here it would be good to explain why normal distribution and not the same log-normal distribution is used in the Monte Carlo simulation (parameter fluctuations).

Response:

Thank you very much for your suggestion regarding the lifespan distribution. In this case, we primarily adopted the log-normal distribution based on Miatto et al. (https://www.sciencedirect.com/science/article/pii/S0921344917300265), where it was noted that "log-normal is preferable for buildings and similar structures."

Following this approach, we also used the log-normal distribution in our previous work on the historical material stock-flow analysis of aggregates in China (https://www.sciencedirect.com/science/article/pii/S0921344922000210), referencing several earlier studies (https://www.sciencedirect.com/science/article/pii/S0921344917300265; https://www.sciencedirect.com/science/article/pii/S0921344919305737; https://www.sciencedirect.com/science/article/pii/S0301421516301276; https://www.sciencedirect.com/science/article/pii/S0921344912002273).

We added paragraphs in the Supplemental Notes to clarify:

The metabolic characteristics of China's buildings and infrastructure stocks inform the selection of the lognormal distribution as the model's probability density function 10,11, as detailed in Formula 2-16. The distribution parameters and their relationships are further elaborated in Formulas 2-17 and 2-18. In previous studies1,11, 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 China10. Also, we follow the previous study12 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.

Regarding the uncertainty analysis, we also used the normal distribution in the Monte Carlo simulation. We identified a typo in the SI related to this, which we have now corrected.

The use of a normal distribution in Monte Carlo simulations is often due to its symmetry. It assumes that variables are symmetrically distributed around the mean, meaning deviations in both positive and negative directions are equally likely, with most values concentrated near the mean. This is a reasonable assumption for estimating data errors and is a common practice in related studies.

2b) It would be useful to include justification of parameter choices or some insight into their feasibility. For example, the extent to which building/infrastructure lifespans can be increased in China.

Response:

Thank you very much.

In our model, we accounted for the increase in building lifespans, with specific data settings sourced from relevant literature. Detailed data can be found in the *Supplementary_Dataset_Parameters.xlsx*. Additionally, we have provided data examples and the corresponding references in the Table S11.

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

<table>
<tr><th>Category</th><th>Sub-Category</th><th colspan="2">Underlying data in 2020</th><th>Material intensity in 2020 (t/unit underlying data)</th><th>Average lifetime (year)</th></tr>
<tr><td rowspan="6">Building</td><td>Residential building (not including the rural house)</td><td rowspan="6">Constructed floor area (kilo square meter)</td><td>59084</td><td>1645</td><td>25(1949–1978)
30(1979–2000)
35(2001–2020)</td></tr>
<tr><td>Commercial building</td><td>15515</td><td>1644</td><td rowspan="5">35(1949–1978)
40(1979–2000)
45(2001–2020)</td></tr>
<tr><td>Office</td><td>5145</td><td>1377</td></tr>
<tr><td>Education & Culture & Healthcare & Research</td><td>6723</td><td>1580</td></tr>
<tr><td>Plant & Warehouse</td><td>6106</td><td>1966</td></tr>
<tr><td>Other buildings</td><td>3309</td><td>1593</td></tr>
<tr><td colspan="2">Waterworks</td><td>Concrete consumption for waterworks (kilo cubic meter)</td><td>347</td><td>1960</td><td>50</td></tr>
<tr><td rowspan="6">Road</td><td>Express highway</td><td rowspan="6">Road length (km)</td><td>1173</td><td>54600</td><td>10</td></tr>
<tr><td>Class I</td><td>1369</td><td>26880</td><td>10</td></tr>
<tr><td>Class II</td><td>3996</td><td>8400</td><td>8</td></tr>
<tr><td>Class III-IV</td><td>15726</td><td>4500</td><td>6</td></tr>
<tr><td>Town road</td><td>11208</td><td>8200</td><td>8</td></tr>
<tr><td>Rural road</td><td>18241</td><td>5729</td><td>6</td></tr>
<tr><td rowspan="2">Railway</td><td>High-speed railway</td><td rowspan="2">Railway length (km)</td><td>431</td><td>120000</td><td>30</td></tr>
<tr><td>General speed railway</td><td>1670</td><td>43000</td><td>30</td></tr>
<tr><td rowspan="2">Rail transit</td><td>Light rail</td><td rowspan="2">Rail transit length (km)</td><td>-</td><td>-</td><td>30</td></tr>
<tr><td>Subway</td><td>754</td><td>70000</td><td>30</td></tr>
<tr><td>Pipeline</td><td>Tap pipe</td><td></td><td>42452</td><td>3300</td><td>30</td></tr>
</table>

	Sewer pipe	Pipeline length (km)	19344	3300	30
Rural house		Rural house area = Rural population * Per capita floor area (kilo square meter)	287746	1253	30
Park etc.		Park area (kilo square meter)	357000	1000	40

Note: See SI for detailed data sources.

(3) The discussion on absolute decoupling of aggregates and GDP over the period of 2016-2020. Some figures appear to contradict the authors' suggestion here.

Response:

Thank you for your question. The distinction lies between stock and consumption, and they are not contradictory.

- The consumption (flow) of sand and gravel has decoupled from GDP, while consumption represents the incremental increase in stock.
- Per capita stock is closely related to economic development (GDP), as the stock of sand and gravel provides essential services to society and is directly linked to the economy.

It may not be very apparent at the starting point in Figure 3, but if you refer to Figures S24-S25, which focus on the period from 2016 to 2020, the decoupling in most regions becomes much more evident.

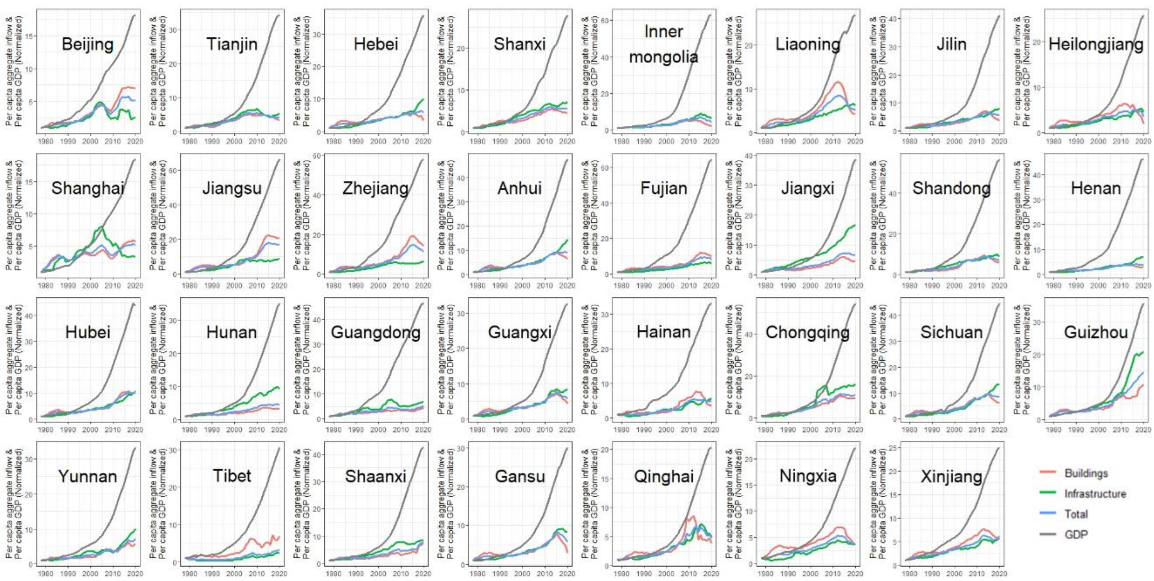

Figure S24 Provincial per capita aggregate demand, and per capita GDP (normalized).

(4) Finally, I feel that the authors must better explain and justify comments made relating to environmental impacts and sustainability. These are important but often mishandled aspects of circularity and sustainable resource management.

Response:

Thank you very much. In the concluding section, based on your suggestions, we have revised the content related to the sand crisis, environmental impacts and sustainability, and the circular economy. The revised content is as follows:

The "large-scale but low-cost" nature of sand and gravel use has led to a sand crisis driving a depletion of a common pool resource, posing not only significant environmental risks but also serious social impacts. Illegal and excessive extraction has worsened the crisis, resulting in habitat destruction, biodiversity loss, and threatening long-term resource availability and ecological balance. China's success in transitioning from natural to manufactured aggregates (crushed stone) through strong policy guidance demonstrates the effectiveness of targeted regulations in mitigating these impacts. Furthermore, by integrating circular economy principles—such as promoting recycled aggregates and utilizing waste materials like tailings—further reductions in primary extraction and environmental degradation can be achieved. Looking ahead, recycling and managing CDW will require continued government support. Strong, evidence-based policy support and local supply-demand plans are essential for addressing sustainability challenges and providing valuable insights for rapidly growing economies.

Detailed comments by line.
(5) Line 33 It is the extraction/use of aggregates that pose environmental challenges not the aggregates themselves.

Response:

Thank you and corrected.

(6) Line 36 Is it worth including a comment on the variation in aggregate demands peaking at the local scale compared to the national scale?

Response:

Thank you and rephased as:

We find that China's aggregate demand peaked around 2015 along with a supply side shift from natural to manufactured aggregates. Total demand is projected to decline to ~50% of 2020 levels in circular economy scenarios. Per capita stocks are *generally projected to reach saturation by 2040 with variations across provinces.*

(7) Line 38 I have an issue with 'we find' here as the shift from natural to manufactured aggregates in China is documented prior to this study, e.g., Z. Ren et al. (2022) (https://doi.org/10.1016/j.resconrec.2022.106173) as cited on line 335: 'China has shifted from natural to manufactured aggregates to meet high demand4'.

Response:

Thank you for mentioning this work. This study by Ren et al. (2022) was also conducted by our team and focuses more on historical analysis, whereas the current paper is aimed at future scenario analysis. We see how this is ambiguous. To avoid any misunderstanding, we have removed the phrase "we find."

(8) Line 40 This is the only use of 'recycled flows' in the manuscript and the only recycled flows in Fig. S3 is 'recycled aggregates'. Perhaps, '... availability of recycled [aggregates]' instead, or re-work the sentence.

Response:

Thank you and corrected.

(9) Line 41 The implications of the results are a little vague.

Response:

Thank you very much. Our primary aim here is to emphasize that due to the unique characteristics of sand and gravel, strong and targeted policies are crucial. However, due to the word limit in the abstract, our current version is as follows:

> *Aggregates (sand, gravel, crushed stone) make up half of all globally extracted materials and present significant environmental challenges. China, which consumes half of the world's aggregates, is undergoing profound shifts in both supply and demand, both now and in the future. Our scenario-based model tracks aggregate flows and stocks across 30 end-uses in Chinese provinces from 1978 to 2050. We find that China's aggregate demand peaked around 2015 along with a supply side shift from natural to manufactured aggregates. Total demand is projected to decline to ~50% of 2020 levels in circular economy scenarios. Per capita stocks are generally projected to reach saturation by 2040 with variations across provinces. Stock saturation may lead to increased availability of recycled aggregates, which could become a primary supply source. We highlight the critical need for stricter policies and regulations for the aggregate industry, offering insights for other economies facing similar challenges.*

(10) Line 53 Feel free to ignore, but something like, 'In China, each cubic meter of concrete typically contains 1.8 tons of aggregates.', might be clearer.

Response:

Thank you and corrected – much better!

(11) Line 55 'For roads, between 4,000 and 30,000 tons...' may be clearer than '4 and 30 thousand tons'.

Response:

Thank you and corrected.

(12) Line 56 As above, '...70,000 – 120,000 tons per kilometre'.

Response:

Thank you and corrected.

(13) Line 62 Low awareness of what exactly?

Response:

Thank you. If referring to years ago, due to the low cost and easy availability of sand and gravel, along with their non-toxic nature and the seemingly minimal environmental impact of extraction, governments and the public did not perceive sand and gravel as valuable resources. They were not considered worthy of legal or administrative protection, and the extraction practices were largely unregulated, with little intervention from authorities despite widespread over-extraction.

(14) Line 65 Clarify that the 'alternatives' are alternatives to sand as the previous sentence ended on waterbody extraction (i.e., extraction / an extraction technology). The topic changes back to sand on Line 65.

Response:

Thank you and we changed it to "alternatives of natural sand".

(15) Line 66 '...offer solutions' 'are more sustainable and less environmentally impactful alternatives...' ?

Response:

Thank you and we changed it following your suggestions.

(16) Line 67 Clarify what 'industrial inputs'. Might be useful to include reference to ecological/ecosystem management practices or their application in this context.

Response:

Thank you very much. Here, "industrial inputs" refer to the processes involved in manufactured aggregates, such as blasting and crushing, which can have environmental impacts. These activities, like quarrying and blasting, require strict environmental management measures (such as China's green mine policies). We have made the corresponding revisions accordingly:

Supply-side changes are important and less environmentally impactful resources include crushed rocks from quarries (crushed stones or manufactured aggregates; see the definition in the Methods section), secondary aggregates from construction and demolition waste (CDW) and ore-sand (a by-product of mineral processing). However, blasting and crushing of rocks or using ore-sand still has environmental impacts18,19, requiring strict management measures, which are more feasible to regulate than widespread illegal extraction of nature sand and gravel.

(17) Line 68 I don't believe aggregates have 'distinctive environmental impacts' as LCA has pre-defined impact pathways depending on the life cycle impact assessment method applied, with potential environmental impacts at the endpoint. If the sentence means to say the potential environmental impacts of traditional and alternative aggregates are different, this can be used to improve 'offer solutions' on Line 66.

Response:

Thank you, we have removed this sentence.

(18) Line 71 Some regions globally?

Response:

Thank you and corrected.

(19) Line 72 Clarify how aggregate shortages lead to environmental and social impacts. Perhaps replacing 'as well as' with 'which drives' – for example – would be sufficient.

Response:

Thank you and corrected. Now it reads:

Local shortages have driven up prices, fueling illegal extraction and exacerbating environmental and social impacts1.

(20) Line 74 Great point – an important limitation for aggregate supply.

Response:

Thank you.

(21) Line 78 The terms 'buildings' and 'infrastructure' in this paper are explained in the supplementary information (Table S1) but it might be useful to clarify the terminology here.

Response:

Thank you and we have added a note here:

See Table S1 for detailed terminology and classification of aggregate final uses .

(22) Line 79 Include reference for limited use of recycled aggregates globally.

Response:

Thank you and we have added following your suggestion.

(23) Line 79 Great point about the restrictions of standards, etc., when trying to re-use aggregates especially in high-quality concrete.

Response:

Thank you.

(24) Line 85 Timely contemporaneous ?

Response:

Thank you and we rephased this part. Now it reads:

Sustainable management of these resources is complicated by a lack of reliable monitoring data on extraction and usage hinders the formulation of effective policies28. This is especially challenging for developing countries29, which are the primary drivers of aggregate demand during periods of rapid development. In these regions, high demand is often accompanied by unregulated extraction practices where robust management policies are lacking.

(25) Line 88 Add reference for the 'boom'

Response:

Thank you and added.

(26) Line 93 Reference for '...nearly half of the global aggregate usage.' ?

Response:

Thank you. Here we have referenced data from UNEP's *Global Resource Outlook*.

(27) Line 93 Add date (year) of the peak and decline. Something more quantitative than 'recent'.

Response:

Thank you and added.

(28) Lines 97 Consider rewording as 'it' here is 'aggregate consumption', from the previous sentence. Rates of... ?

Response:

Thank you and we reworded it as:

The dynamics of aggregate consumption also highlight the global importance of construction material flows for the world's and China's metabolism, as evidenced by historical data and projected scenario-based time series37.

(29) Line 101 Clear research motivation – good. The paper focuses on the production and use of recycled aggregates.

Response:

Thank you.

(30) Line 106 Refer the reader to the supplementary map that shows China's provinces (Figure S2)?

Response:

Thank you and added.

(31) Line 107 Flows and stocks?

Response:

Thank you and added.

(32) Line 108 Generally, nice sentence about CHAMPS' potential impact.

Response:

Thank you.

(33) Line 109 '...under [X modelled] scenarios' ?

Response:

Thank you and we added the number here. In total we have six main scenarios.

(34) Line 110 '[Greater] sustainability' maybe?

Response:

Thank you and we rephased it as:

> *CHAMPS enables a comprehensive understanding of the historical, current, and future dynamics of aggregate supply and usage across mainland China and its 31 provinces (see Figure S2) between 1978 and 2050. It is a dynamic model that tracks the flows and stocks of materials across their entire lifecycle and various uses. We include 30 distinct end uses which are divided into eight categories. We project trends to 2050 under six main scenarios and explore how circular economy approaches can be effectively applied in the aggregate industry.*

(35) Line 112 Five not four strategies are listed: IU, LD, LE, CD, and AM. Are these

‘strategies’ the aforementioned ‘scenarios’ ?

Response:

Thank you for the clarification.

The strategies and scenarios are not entirely the same. A scenario can represent a combination of multiple strategies. The AM scenario is a combination of four strategies, while the other four scenarios each correspond to a single strategy. We have four independent strategies: IU, LD, LE, and IR, and five main scenarios: IU, LD, LE, IR, and AM.

(36) Line 115 IU, LD, LE, and CD incorporate only one R. Maybe ‘aspects of the circular economy’s core principles...’ or similar.

Response:

Thank you and corrected.

(37) Line 118 Tell the reader where in the Supplementary Notes to find the full specs. Table 1 In the LD entry: ‘... used per unit of final use.’ Would ‘per functional unit (e.g., one house)’ be a useful alternative here?

Response:

Thank you and corrected.

(38) Line 126 Ref 37 check ###

Response:

Thank you and we checked the ref 37.

(39) Line 128 Various scenarios? [the modelled scenarios]?

Response:

Thank you and corrected.

(40) Lines 131 - 134 I think the ; and . are errors that confuse this summary of results.

Response:

Thank you and corrected.

(41) Line 136 Remove ‘with estimates ranging’ ?

Response:

Thank you and corrected.

(42) Line 139 Nice point about changing trends in asset investment.

Response:

Thank you.

(43) Line 147 Imminent demolition? When are buildings/infrastructure expected to be at end-of-life?

Response:

Thank you for this comment. China's aggregate demand remained high between 2010 and 2020, followed by a sharp decline. Considering the typical lifespan of buildings and infrastructure in China, which we estimate to be around xxx years based on a log-normal distribution, we anticipate a rapid acceleration of aggregate waste flows between 2030 and 2040. We have revised the text to reflect this as follows:

> *With the saturation of China's construction industry and the ensuing asset retirements, demolition waste is expected to accelerate in the coming future46,47.*

(44) Line 153 Is this saying road related infrastructure will contribute 39% of total outflows (construction waste?) by 2050? This could be more explicit, if the word count allows.

Response:

Thank you for pointing this out. To clarify, infrastructure as a whole will account for 39%, with roads being the largest contributor within that category. We rephased the sentence:

> *Infrastructure (predominantly road-related) is expected to contribute 39% of the total outflows.*

(45) Line 154 Good point

Response:

Thank you.

(46) Line 155 The authors suggest recycling CDW can alleviate environmental impacts. I think this is instead 'can mitigate environmental impacts (of [primary] aggregate extraction]'.

Response:

Thank you and we rephased the sentence:

Nevertheless, recycling CDW from these aggregates offers a pathway to alleviate the environmental impacts of primary aggregate extraction and reduce the reliance on extraction49,50.

(47) Figure 1 Can the figures be started at x = 0, y = 0 as there are no negative y-values in A, B, and C ?

Response:

Thank you for your suggestion. The current figures are standard for R-generated plots. Given that there are no negative values and the plots align with typical conventions, we would prefer to keep them as they are if that's acceptable.

(48) The current format is likely an aesthetic choice. It would be useful to have keys in all panels or make clear if that in Fig.1B applies to Fig.1A and Fig.1C. Perhaps describe the colours in the caption to make the figure stand-alone?

Response:

Thank you and we have updated Figure 1 following your suggestions.

Fig. 1 Overview of Aggregate Flows (A, C), Stocks (B), and Associated Economic Indicators (D) in China. (A) China's aggregate demand from 1978 to 2050; (B) Aggregate stocks in China from 1978 to 2050; (C) Aggregate waste generation in China from 1978 to 2050, with aggregate demand projections under the All Measures scenario; (D) Growth rates of aggregate demand (in blue), cement consumption (in yellow), fixed asset investment (in grey), and GDP (in red) in China between 2000 and 2020. The growth rate data in (D) is plotted using a 3-year moving average. Fig. 1 (A, B, C) share the legend shown in Fig. 1B. Dark purple indicates aggregates used in historical buildings, dark grey for historical infrastructure, light purple for future buildings under the All Measures scenario, and light grey for future infrastructure under the same scenario. Different colours in D correspond to historical data and future scenarios: blue represents historical data, orange represents the Baseline scenario, green represents the Intensive Use *intervention, pink represents the Lightweight Design intervention, brown represents the Lifetime Extension intervention, and red represents the All Measures scenario.*

(49) Line 166 A clear subheading will clarify the framing of the subsequent text. ‘Recycled aggregates [can] bridge the circularity gap [in China]’ ‘[The use of] recycled aggregates to bridge the circularity gap [in China]’

Response:

Thank you and updated it following your suggestion!

(50) Given the first paragraph references past work/results, perhaps the second edit is closer to the authors’ intended meaning?

Response:

Thank you and we choice this subtitle as you suggested:

Recycled Aggregates can Bridge the Circularity Gap

(51) Line 170 Rather than ‘evolution’, how about ‘transition from sand and gravel to crushed rock’?

Response:

Thank you and we update these in the manuscript:

The transition from natural aggregates to manufactured aggregates (crushed stone) is particularly noticeable over the past two decades ...

(52) Line 178 Environmental impacts here are again vague / the sentence could be improved.

Response:

Thank you and we improve the sentence:

While this transition mitigates environmental and social concerns related to water-based sand mining, it introduces new challenges, primarily the ecological impacts of mountain quarrying on nearby ecosystems, with relatively minor impacts from processing stages6,55.

(53) Line 181 Consider rewording ‘the use of outflows in circularity’. E.g., ‘the [circular use] of outflows’ or ‘the use of outflows for circularity’ ?

Response:

Thank you and updated it following your suggestion.

(54) Line 182 Which scenarios show this?

Response:

Thank you. The IR or AM scenarios (which includes IR). We rephased the sentence to make this clearer:

Scenario analysis indicates that Improved Recycling (IR) interventions can substantially increase recycled aggregate supply from 2021 to 2050, positioning it alongside crushed stone as a dominant source of aggregate supply.

(55) Line 183 Am I right in saying the ‘supply of recycled aggregates’ here is their availability / their return to market but not necessarily their use?

Response:

Thank you. It is.

(56) Line 186 The data is in Figs S5-S8 but guide the reader to the discussion/analysis of those results.

Response:

Thank you. Figures S5-8 provide an overview of our model framework. We have revised the wording in the article to be more precise.

(57) Line 193 Clarify in the text what comprises ‘total waste’ (as in Fig. 2D) ?

Response:

Thank you. The term "total waste" here refers to CDW, which corresponds to building demolition waste, infrastructure demolition waste, and construction waste in Figure 2D. We have revised the sentence for clarity:

Recycling of aggregate waste in China is expected to rise from 733.7 Mt in 2021 to 4.5 Gt by 2050 under the All Measures scenario, increasing its share from 13% to 46% of total CDW generation (Figure 2D).

(58) Line 199 Again, benefits re environmental impacts and sustainability are mentioned without adequate (in my opinion) explanation. There is no reference here even.

Response:

Thank you. We have revised the wording and also referenced the UNEP report on sand and aggregates:

> *This significant shift is likely to dramatically reduce environmental impacts6,10,56.*

(59) Lines 205-211 There is a mixture of mass and percentage values. 55% decrease then 6.0 Gt reduction then 4.5 Gt 'surge'. Consistency would enable comparison.

Response:

Thank you for your suggestion. We have revised the comparison of percentages and absolute quantities to improve clarity:

> *Primary aggregate extraction is projected to decrease by 55% under the All Measures scenario by 2050, equivalent to a reduction of 6.0 Gt compared to the Baseline (Figure 2C). This reduction is driven by strategies focusing on Intensive Use, Lightweight Design, Lifetime Extension, and Improved Recycling. Currently, with a recycling rate below 20%, there is significant room for improvement. By fully implementing 3R measures, the share of recycled aggregates is expected to rise to 48% of total demand by 2050 under the All Measures scenario, with the volume reaching 4.5 Gt.*

(60) Figure 2 I'm not sure Fig.2A shows recycled aggregates surging in the forecast section, especially compared to the increase shown for crushed rocks between 2000 and 2010. Perhaps a less emotive word?

Response:

Thank you for pointing this out. You're right, the proportion increases, but the absolute volume does not surge due to the overall decrease in aggregate demand. We have revised the statement accordingly:

> *By fully implementing 3R measures, the share of recycled aggregates is expected to rise to 48% of total demand by 2050 under the All Measures scenario, with the volume reaching 4.5 Gt.*

(61) Fig. 1B – why are only three dates shown across the 1978-2050 scope?

Response:

Thank you for this question. These three are key years that illustrate the shifting structure of natural aggregates, manufactured aggregates, and recycled aggregates on the supply side. Data for the intermediate years can be found in Fig. S27. We have also included this explanation in the figure description for clarity.

(62) Fig. 1D is nice – a good use of Sankey – but it could be neatened up a little (editorial comment as the information is conveyed as-is).

Response:

Thank you for your positive feedback on Fig. 1D. We believe the current version effectively conveys the necessary information. However, if you have specific suggestions on how we could improve the layout, we would be happy to consider them.

(63) Line 222 Highlights [differences] in... ?

Response:

Thank you. We have revised the sentence to emphasize these differences as follows:

> *The distribution of aggregate stocks and flows across China's provinces highlights the economic diversity and development of each region, particularly reflected by their stage of development, construction demand, development plans, and resource endowments57.*

(64) Lines 222- 225 Nice!

Response:

Thank you!

(65) Lines 227-231 I think this is the only use of the terms 'investment-driven' and 'infrastructure-driven'. Investment-driven is more intuitive, but infrastructure-driven – demand driven by infrastructure needs (I think) – needs further explanation.

Response:

Thank you! We have made adjustments to the wording and have provided further clarification.

Meanwhile, growth driven by infrastructure needs remained relatively stable (green lines in Figure 3), as infrastructure projects are typically aligned with long-term development plans and are not arbitrarily constructed. The demand for aggregates from infrastructure is also relatively modest compared to real estate. In contrast, the real estate sector is more market-driven. During certain periods in China (e.g., post-2007), the land economy model has seen the government directly or indirectly encouraging real estate development59.

(66) Line 239 Is there a reference or specific result(s) that confirm differences in demand drive the disparity?

Response:

Thank you for pointing this out. The specific results can be found in Figures S13-14. We have also added this clarification to the main text.

(67) Line 257 Re-structure sentence to remove 'they', e.g., 'Per capita stocks ranged from...'

Response:

Thank you and corrected.

(68) Lines 260-261 Here, 'lead to' suggests causality - is this a confident assertion made from the results? Are other (interdependent) factors at play? Alternatively, change 'lead to' to 'contribute to' or similar.

Response:

Thank you and we changed it to "contribute to" and added a reference.

(69) Line 269 GDP increases across all provinces in Figure S24 and Figure S25 and total aggregate demand in Figure S24 and aggregate inflows in Figure S25 have a more gradual net increase. Yes. It might be prudent to clarify relative decoupling here.

Response:

Thank you for the suggestion. Regarding decoupling, the "Demand" here refers to flow, which has been generally decreasing over the past five years, so we could argue that it reflects absolute decoupling. In terms of stock, it may be more appropriate to describe it as relative decoupling. However, we have removed the term "absolute" to make the statement more nuanced.

(70) Line 271 Consider some adjustment around, 'as the economy...', to distinguish the two points made: (i) the essential role of aggregate stock in supporting development, and (ii) the move away from rapid stock growth now that the economy is (suggested by decoupling and steadier GDP) at a point where existing infrastructure/buildings are sufficient.

Response:

Thank you. Based on your suggestion, we have made the following adjustments:

We can see the decoupling of aggregate demand from GDP (Figure S23-25), showing that: (i) aggregate stock is crucial in supporting economic development and essential services (like hospitals and health outcomes), and (ii) the economy now relies more on the value of existing infrastructure rather than rapid stock growth.

(71) Line 272 Which provinces are the authors referring to re absolute decoupling? No figures or data are referenced here. The authors provide a good definition of absolute decoupling here. However, the plots in Figures S24 and S25 do not all show a decrease in aggregate demand between 2016 and 2020. Guangdong and Guizou (in both Figs S24 and S25), for example. Perhaps the authors mean that at points within the period 2016-2020, there is some absolute decoupling? Further clarification is required here.

Response:

Thank you for this important comment. Here, we found that many provinces have achieved absolute decoupling, such as Beijing, Tianjin, and Shanghai. As you mentioned, Figures S23-25 can illustrate this. Provinces like Guangdong and Guizhou have not yet achieved absolute decoupling, but these are exceptions. Most provinces have decoupled. Additionally, we previously noted that provinces like Guizhou and Guangdong have not yet reached peak aggregate demand. If the demand hasn't peaked, it means it hasn't decreased, so absolute decoupling hasn't occurred. Given that this analysis covers a relatively short period, we removed the term "absolute" to avoid confusion.

(72) Line 278 Demographics can suggest more than population (number of individuals). Do the authors mean to include population characteristics (e.g., age, race) here?

Response:

Thank you. We have not included other population indicators. We have revised the text to use "populations."

(73) Line 292 Potentially meeting – what are the requisites and barriers?

Response:

Thank you for this comment. "Potentially" is simply used to indicate the future possibility, suggesting the potential structure under this scenario. The premise is that a circular economy could be developed to support aggregate recycling.

(74) Line 296 I'm not sure about, 'waste generation is expected to exceed demand' – is there a demand for waste ? For recycled aggregates?

Response:

Thank you. The term "demand" refers to the total aggregate demand. We have made adjustments in the text accordingly.

(75) Line 297 Does 'excess waste' suggest a shift towards more sustainable, circular models? Again, what is the likelihood of this and its requisites/barriers ? It is possible that excess waste results in increased landfill, especially if usable waste (recycled aggregate) is generated far from potential users.

Response:

Thank you for this insightful perspective. Indeed, as you mentioned, the generation of large amounts of waste creates opportunities for circular development. When economic and social development reaches a stable phase, from the perspective of a single resource's social metabolism, the inflow and outflow of stock should roughly balance out, allowing recycled resources to play a more prominent role.

Thus, it is not the excess waste that drives circular development, but rather the possibility of such development arises naturally when society and the economy reach a certain stage.

Over the long term, waste generation is constrained by the inflow of stock, and when stock inflows are no longer at high levels, waste generation will naturally stabilize, eliminating the risk of an oversupply of recycled aggregates. Even if a temporary oversupply of recycled aggregates occurs in more developed regions, this can be addressed by opening up interregional markets for recycled aggregates, helping to absorb the excess supply.

Based on your suggestion, we have revised the text as follows:

Waste generation is expected to exceed aggregate demand in 22 provinces by 2050 under All Measures scenario, particularly in the saturated construction markets of the east and northeast, highlighting the necessity of embracing circular economy practices and finding environmentally friendly ways to manage the surplus waste aggregates, such as through interregional redistribution.

(76) Figure 3 Add a key / explanation in the caption.

Response:

Thank you. We have added explanations for the lines and colours.

(77) Figure 4B This may simply be my inexperience with this plot, but I find it difficult to understand what the widths convey given there are no x-values. Why only 2020 and 2050 across the modelled period of 1978-2050?

Response:

Thank you. This is a violin plot showing the distribution of per capita aggregate demand across provinces for a single year. The plot presents the distribution of aggregate demand for housing and infrastructure across Chinese provinces for the years 2020 and 2050. Red represents the data for 2020, and blue represents the data for 2050. On the x-axis, the two plots on the left represent housing, while the two on the right represent infrastructure. In the violin plot, the thicker areas indicate a higher concentration of values at the corresponding position on the y-axis.

Here, we can see that by 2050, the per capita demand for aggregates across provinces will become more uniform compared to 2020, with smaller differences between provinces, whether in the building or infrastructure categories.

We added a sentence to explain this in the manuscript:

In 2050, per capita aggregate demand across provinces will be more uniform compared to 2020, with smaller differences in both the building and infrastructure sectors.

(78) Line 319 '...often [reflects] levels of...' maybe?

Response:

Thank you and corrected.

(79) Line 325 Some words missing around 'All Measures'

Response:

Thank you and corrected.

(80) Line 338 Check wording of 'to mitigate sand scarcity sustainability'. Just 'sand scarcity' maybe? You want to mitigate scarcity and achieve sustainability.

Response:

Thank you and we corrected it as you suggested.

(81) Line 340 Great point again, yes. But for context, is this what China is moving towards: high-value construction?

Response:

Thank you. Yes, this is more precise. We have changed it to 'high-quality construction.' Currently, China emphasizes high-quality development, with policies focusing on high-quality buildings to avoid excessive demolition and reconstruction.

(82) Line 340 More policies? Better policies? Previously the authors mentioned policies re a shift from natural to manufactured aggregates.

Response:

Thank you for this point. We believe it should be 'more policies' or 'further policies' or ‘forward-thinking’. China has indeed implemented policies promoting the transition from natural sand to manufactured aggregates. There are no inherently good or bad policies; rather, the best policies are those that evolve with the times. The focus has shifted from transitioning to manufactured aggregates to now promoting the development of recycled aggregates.

(83) Line 347 Would the technology ‘increase the market’s acceptable of recycled aggregates’ or rather increase capacity to produce recycled aggregates to satisfy e.g., material/building standards?

Response:

Thank you for this point. Technology plays a decisive role, and under this premise, market acceptance largely depends on cost and practicality, along with some socioeconomic soft factors. However, to truly improve market acceptance, the market itself and policy guidance, as forms of soft support, are essential. However, the technology is the premise.

(84) Line 348 Why tax incentives first and foremost rather than aforementioned policymaking? Provide examples where taxation has benefited market acceptance of recycled aggregates, to justify this suggestion.

Response:

Thank you for the clarification. There may be a miscommunication here. We are not suggesting a comparison between the importance of tax reductions, subsidies, and policy measures. Instead, we want to highlight concrete policy recommendations such as tax reductions and subsidies.

(85) Line 351 ‘Green practices’ is vague (green washing term). Consider expanding upon this point and clarifying whether the use of recycled aggregates is a green practice (based on environmental impact mitigation, economic circularity, etc.).

Response:

Thank you for pointing this out. In China’s sand and gravel industry, green practices primarily refer to intelligent operations, environmental protection, high quality, effective management, large-scale operations, ecological approaches, and the transition to a circular economy. We have made some additions to the text to reflect this.

Currently, the concept of green mines in China does not emphasize recycled aggregates, as the industry is still in the process of transitioning towards manufactured aggregates. However, in a broader sense, recycled aggregates should also fall under the umbrella of green development and will need to be incorporated into future policy frameworks.

We have revised this part:

China's "green mine" policy promotes key strategies such as subsidies for intelligent operations, environmental protection, high-quality production, and effective management. It encourages large-scale ecological operations and the shift to a circular economy. Recognition programs and targeted incentives for innovators further support these goals66. Effective collaboration across technical, policy, and academic institutions will be needed to guide and monitor the development of a recycled aggregate market.

(86) Line 355 This final ‘future work’ sentence feels a bit vague/an add-on. Can it be linked to this research topic more specifically?

Response:

Thank you, we have made some adjustments based on your suggestions:

The “large-scale but low-cost” nature of sand and gravel use has led to a sand crisis driving a depletion of a common pool resource, posing not only significant environmental risks but also serious social impacts. Illegal and excessive extraction has worsened the crisis, resulting in habitat destruction, biodiversity loss, and threatening long-term resource availability and ecological balance. China's success in transitioning from natural to manufactured aggregates (crushed stone) through strong policy guidance demonstrates the effectiveness of targeted regulations in mitigating these impacts. Furthermore, by integrating *circular economy principles—such as promoting recycled aggregates and utilizing waste materials like tailings—further reductions in primary extraction and environmental degradation can be achieved. Looking ahead, recycling and managing CDW will require continued government support. Strong, evidence-based policy support and local supply-demand plans are essential for addressing sustainability challenges and providing valuable insights for rapidly growing economies.*

(87) Lines 358-359 The align comment: are the authors meaning that their results agree with the previous study's findings at the global scale? The topic sentence is about crushed stone production but the paragraph continues on about aggregate demand.

Response:

Thank you, this is meant to highlight the consistency between the findings of this study and previous global research. We have adjusted the phrasing as follows:

China's shift in aggregate sources—from natural aggregates to crushed stone—is contributing a global trend in which worldwide crushed stone production may peak between 2020 and 2030.

(88) Line 361 Commas: natural sand, gravel, and crushed stone

Response:

Thank you and corrected.

(89) Line 363 Due to peak?

Response:

Thank you. There is some ambiguity here, so we have adjusted:

. However, previous work1 also finds that the global peak demand for aggregates is likely to occur between 2060 and 2070, primarily driven by the population reaching or nearing its peak.

(90) Line 364 It's it is (avoid contractions)

Response:

Thank you and corrected!

(91) Lines 364-367 Link to previously identified issues with aggregate supply? 'Given X, Y, and Z associated with..., it is crucial to...'

Response:

Thank you and we rephased here based on your suggestions:

Given the challenges associated with aggregate supply, including social and environmental impacts on natural aggregate extraction and rising demand, it is crucial to assess how urban development and the need for sustainable aggregate supplies will evolve in developing regions such as the Middle East, Africa, South Asia, and South America. These areas might become the main markets for aggregates in the future.

(92) Line 367 While China's transition to manufactured aggregates provides a model for other developing countries to follow, there will be other examples worth mentioning, and location-specific requirements that might make other transitions more practical in the developing regions.

Response:

Thank you. Based on your feedback, we have adjusted the wording as follows:

China's transition to using more eco-friendly, manufactured aggregates (crushed stones) as a substitute for river and lake sand can serve as a valuable model for others. However, regional differences may require alternative approaches. It remains uncertain if there are sufficient and accessible rock quarries in every area to follow this model since transporting aggregates or rocks over long distances, whether recycled or extracted, is costly.

(93) Line 378 This is true for all countries (and local areas given the importance of regional perspectives, per Line 374), not just developing countries.

Response:

Thank you and we agree with you.

(94) Line 380 Clarify and evidence how Material Flow Analysis (MFA) contributes to 'standardisation' and 'regulation' within developing countries. MFA can improve understanding of stocks and flows but cannot by itself provide data on potential impacts of aggregate extraction/use/etc – this requires e.g., LCA.

Response:

Thank you, we agree with your point. We have made some adjustments:

Conducting a material flow analysis is foundational to this process as it enhances the understanding of resource stocks, flows, and extraction-processing-use landscapes at the regional scale. Integrating MFA with life cycle assessment results allows for a more comprehensive assessment of these impacts and the identification of potential mitigation strategies. This approach enables a more comprehensive evaluation of sustainability challenges and opportunities in the aggregate industry which includes both a supply- and demand-side perspective.

(95) Line 384 Yes, excellent point

Response:

Thank you!

(96) Line 385 'GIS data' rather than 'GIS perspective'?

Response:

Thank you and corrected.

(97) Line 387 Are the authors claiming the locations of aggregate stocks were not known prior to this study? Is the statement that GIS enables temporal data to be aggregated for analysis the CHAMPS?

Response:

Thank you for your comments, which allow us to clarify that previous research did not provide a high-resolution distribution of aggregate social stock. GIS offers high-resolution spatial distribution maps for various end uses, and our CHAMPS model is linked to these uses. By combining our model results with GIS data, we can generate detailed information on aggregate stock, demand, and waste generation at a high resolution (Figure S34).

(98) Lines 387-389 Again the ending feels a bit vague / not as punchy as it could be. It could be linked to the development of CHAMPS more.

Response:

Thank you for this. The CHAMPS model progresses from national-level historical analysis to national-level scenario analysis, then to provincial-level historical analysis, and finally to provincial-level scenario analysis. In addition, supply-side scenarios have been incorporated, and now we are exploring the model's application with high-resolution GIS data. By integrating GIS in the future, we can more accurately pinpoint site-level information on extraction, use, decommissioning, and recycling, enabling the model to have a more tangible impact.

We have made some adjustments:

The CHAMPS model we present, combined with Geographic Information Systems (GIS) data, can help identify high-resolution local usage patterns that are relevant to policymakers. For instance, in the Jing-Jin-Ji area, GIS reveals the exact locations of aggregate stocks (Figure S34). By integrating GIS in the future, we can more accurately pinpoint site-level information on extraction, use, decommissioning, and recycling, enabling the model to have a more tangible impact.

(99) Lines 391-393 Tax incentives are no longer suggested – omission or change of heart?

Response:

Thank you. Here, we want to emphasize the importance of government supports like subsidies and policy guidance. We have made some adjustments and additions:

The "large-scale but low-cost" nature of sand and gravel use has led to a sand crisis driving a depletion of a common pool resource, posing not only significant environmental risks but also serious social impacts. Illegal and excessive extraction has worsened the crisis, resulting in habitat destruction, biodiversity loss, and threatening long-term resource availability and ecological balance. China's success in transitioning from natural to manufactured aggregates (crushed stone) through strong policy guidance demonstrates the effectiveness of targeted regulations in mitigating these impacts. Furthermore, by integrating circular economy principles—such as promoting recycled aggregates and utilizing waste materials like tailings—further reductions in primary extraction and environmental degradation can be achieved. Looking ahead, recycling and managing CDW will require continued government support like subsidies and policy guidance. Strong, evidence-based policy support and local supply-demand plans are essential for addressing sustainability challenges and providing valuable insights for rapidly growing economies.

(100) Line 396 Ref for 'no unified definition'?

Response:

Thank you for the question. Yes, the 2022 UNEP report "What is sand? Results from a UNEP/GRID-Geneva expert discussion (https://unepgrid.ch/storage/app/media/Publications/3.%20FINAL_GSOI-GSA-2022-002_What%20is%20sand.pdf)" highlighted this issue, which is why we took the time to clarify the definition of sand and gravel both in the main text and in the supplementary information.

(101) Line 400 Rephrase this sentence – I don't think it quite makes sense/can be clearer.

Response:

Thank you and we removed this.

(102) Line 406 Would be good to have a reference for recycled aggregate quality can match that of virgin aggregates – especially given the aforementioned issues with separation/re-use in high-quality infrastructure.

Response:

Thank you. We have added the references in the main texts:

https://www.sciencedirect.com/science/article/pii/S030438941931516X

https://www.sciencedirect.com/science/article/pii/S2214785320385837

https://www.sciencedirect.com/science/article/pii/S2214785323012658

(103) Line 423 Consider restructuring this bit. Tailings are omitted here because their rate of use is negligible in China/this study?

Response:

Thank you very much for this. Reviewer 3 raised some points on tailings also and so we have outlined some further details on tailings within the model (tailings are included in the model but not separately categorized). As a result, we have added a discussion on tailings in the main article, with additional insights provided in Supplemental Notes 3.9. The relevant paragraph in the paper is as follows:

Additionally, ore-sand (from tailings and waste rock) is considered part of the broader category of manufactured aggregates67.However, the share of ore-sand in aggregate production in China remains relatively low (less than 2%). This is primarily due to concerns over potential pollution risks, excessive density, and recommendations to prioritize tailings for extracting valuable metals instead. It is reported that the stockpile of tailings and waste rock in China has reached 60 billion tons68, which may become an alternative source of natural aggregates in the future. However, detailed statistics and research on tailings ponds are severely lacking69, and whether or how to use these materials still requires further investigation (see Supplemental Notes 3.9 for extended discussion).

(104) Line 427 Is there scope to put the framework (Figure S3) into the main text ?

Response:

Thank you. Considering the word and space limitations, we may have to include it in the SI.

(105) Line 428 Can the five stages be presented more clearly or as bullet points? It currently looks like there are seven not five items.

Response:

Thank you and updated. Extraction, processing, and manufacturing are all preliminary steps that are typically done in one continuous process, which is why we have always considered them as one unit.

(106) Line 448 SSP2 is first mentioned here. Add a reference or explanation.

Response:

Thank you and the reference is added.

(107) Line 456 Reference is this is an established analysis model type, or refer the reader to supplementary discussion – this may be the later referral on Line 460.

Response:

Thank you. This is a newly developed model, and we have provided an explanation of CHAMPS in the SI.

(108) Line 464 Adds plus (i.e., +) Eqs 1, 2 Define coefficients / nomenclature

Response:

Thank you and corrected.

(109) Line 469 Justify the decision to use the log-normal distribution function in this study. Even if 'established best practice'. Eq. 3 Define coefficients/nomenclature

Response:

Thank you for your suggestion regarding the lifespan distribution. In this case, we primarily adopted the log-normal distribution based on Miatto et al. (https://www.sciencedirect.com/science/article/pii/S0921344917300265), where it was noted that "log-normal is preferable for buildings and similar structures."

Following this approach, we also used the log-normal distribution in our previous work on the historical material stock-flow analysis of aggregates in China (https://www.sciencedirect.com/science/article/pii/S0921344922000210), referencing several earlier studies (https://www.sciencedirect.com/science/article/pii/S0921344917300265; https://www.sciencedirect.com/science/article/pii/S0921344919305737; https://www.sciencedirect.com/science/article/pii/S0301421516301276; https://www.sciencedirect.com/science/article/pii/S0921344912002273).

(110) Line 478 Established social metabolism model is mentioned. What is the tailored social metabolism model for the future scenarios? Eq. 4 The term ‘saturated stock’ is used once in the SI and once in the main text (here, Eq. 4). This term needs to be explained along with the other nomenclature in Eq. 4.

Response:

Thank you for the comments. In the scenario analysis, while the basic principles of the social metabolism model remain consistent, several adjustments were made to tailor the model for future scenarios. For instance, we transitioned from a historically stock-driven model to a future stock-driven model and from a historically flow-driven approach to a future stock-driven one. Additionally, the 30 end-use subcategories in the historical model were consolidated into 17 for future scenarios.

Regarding the use of the term "saturated stock" in Eq. 4, we have clarified its definition along with other nomenclature in the equation. We have also expanded the descriptions of the formulas used to provide further clarity. These adjustments should make the model framework more transparent and easier to follow.

(111) Line 490 Is ‘densities’ here describing probabilistic (log-normal) distributions of aggregate flows?

Response:

Thank you. To clarify, in this context, "density" primarily refers to the density associated with various end uses, such as population density, built-up area density, etc. For example, urban road density is calculated as the total length of urban roads divided by the built-up area of the city. We have clarified in the main text:

> *The methodology begins with calculating historical per capita stocks or densities across diverse applications (e.g., population density and built-up area density: urban road density is calculated as the total length of urban roads divided by the built-up area of the city), subsequently establishing future targets grounded in relevant plans and documents.*

(112) Line 492 Sounds good but add a reference the fact economic growth typically follows an s-shape curve linking to the sentences on Lines 493-494.

Response:

Thank you and we have added references.

(113) Line 517 The reader is referred to Section 2.4, Supplementary Notes, for details on specific parameter settings. Following this re housing lifespan, there appears to be a need to better justify assumptions or at least give some insight into the likely future lifespan of buildings/infrastructure and their upper limits. Are there general limitations? China-specific limitations? This is lacking, e.g., '...this study assumes a 90% extension in the service life of new housing constructions from 2021 to 2050, based on the 2020 benchmark.' I extend this comment to all assumptions/parameters in the scenario analysis.

Response:

Thank you for your comment.

Although housing is generally associated with a 70-year property ownership period in China, this is not strictly enforced. Historically, many residential buildings have been demolished after only 30 to 40 years.

The assumptions used in the scenarios are explained in Section 2.4.1 of the SI:

> *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.*

Also, detailed values are provided in the "Scenarios on the demand side" sheet of the Excel dataset. To compare these with historical data, you can refer to the "Historical lifetime expectation" sheet, which shows the changes in lifespan expectations over time.

(114) Line 553 Why is a normal and not log-normal distribution used for the uncertainty analysis?

Response:

Thank you for your question. In the Monte Carlo simulation, random numbers are generated using a normal distribution. We randomly generated 1,000 sets of parameters within the ±10% range and ran 1,000 simulations. However, when each set of parameters is used in the simulation, the CHAMPS model still applies the log-normal distribution. These two concepts are not in conflict. The normal distribution applies to the Monte Carlo simulation for uncertainty analysis, while the log-normal distribution applies to the function in CHAMPS.

We further discuss it in Section 1.5 of the SI:

Regarding the rationale for employing the normal distribution in Monte Carlo simulations, it is based on the assumption that the uncertainties of variables are symmetrically distributed around the mean. This suggests that deviations in both positive and negative directions 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 a common practice (https://www.pnas.org/doi/full/10.1073/pnas.1613773114).

(115) Lines 557-559/Figs. S28-S33 The uncertainty analysis plots are too small / hard to read.

Response:

Thank you. We increased the font size and rotated the page.

(117) Line 592 Supplementary information section could be restructured to make it clearer, naming the files and their contents.

Response:

Thank you, we have made the adjustments accordingly.

(116) Reviewer #4 (Remarks on code availability): I took a look at the code but coded models are not where my experience lies. I do not have experience with R and hence do not have the environment to run the code. Therefore, my observations do not include whether the code operates fully. The README text clarified that the code is not provided in its entirety, which hinders repeatability. The equations presented in the manuscript appear present within the code, suggesting it is a functional and corresponding codebase for the CHAMPS model. I did not locate any Plot() commands suggesting that the codebase does not output visual results and that figures must be created by the end user using output data.

Response:

Thank you for your review and observations. We appreciate your feedback on the code availability. We understand the concern about the completeness of the code provided. The core functionalities and models, including the CHAMPS model of one region, are fully implemented in the code we provided. The additional code for plotting and visualization, which can be quite complex and specific to our setup, is not included as it was deemed non-essential for replicating the model's results. The code outputs all the necessary data for generating the figures. As the visualization code can be quite intricate and specific, we chose not to include it in the main repository. However, the figures can be created using the output data, and this approach helps keep the provided codebase focused on the core functionalities.

Once again, we deeply appreciate your thorough review of our manuscript and supplementary information. Your valuable and important feedback has truly enhanced the quality of our article, and we are very grateful for it.

Response to Reviewer #1:

The authors have made great effort to revise the manuscript, it is easier to understand than the previous version. Following are some suggestions to improve the paper

Response:

Thank you for your constructive comments and insightful suggestions. We have carefully addressed each point raised, which has substantially enhanced the clarity and quality of our manuscript.

1) We find that China's aggregate demand peaked around 2015 along with a supply side shift from natural to manufactured aggregates. Is the aggregate peak and the shift happened at the same year?

Response:

Thank you for this comment. The supply-side transition from natural to manufactured aggregates was a gradual and ongoing process, which we identified as starting around 2010. This indicates it occurred well before the 2015 demand peak. We have revised the sentence in the abstract as follows:

Line 36: We find that China's aggregate demand peaked around 2015 along with a gradual and ongoing supply-side shift from natural to manufactured aggregates.

2) Total demand is projected to decline to ~50% of 2020 levels in circular economy scenarios. Which year is this total demand? is it 2050?

Response:

Thank you for highlighting this. We have clarified the statement as follows:

Line 37: Total demand after 2030 is projected to decline to ~50% of 2020 levels in circular economy scenarios.

3) I wonder if there is study about recycled aggregates globally? how is the technology? how much is the cost? Currently the recycled aggregates in China is not so popular, most of them leads to landfill.

Response:

Thank you for these questions. We have extended our review and we have included more details on this in our extended discussion in the SI 3.10 section:

Line 1244: Internationally, there has been extensive research on recycled aggregates (RA). Li et al.50 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 surface71, which weakens the bond between RA and cement, leading to inferior performance compared to primary aggregates72. RA surface pore structure73,74 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 durability75.

According to Harish et al.51, 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 aggregates76. 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 distance77.

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 growth76.

(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%43,45,50.

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 policies78-80.

Thirty-five pilot cities have achieved around 50% resource utilization—15 percentage points higher than before the pilot projects—indicating substantial room for growth45. Should China reach European, North American, or Japanese recycling levels, the RA market could exceed one trillion RMB81, representing significant opportunities for further development.

Also, we added a few lines to explain this briefly in the discussion:

Line 377: From a technical perspective, the key difference between recycled aggregate (RA) and natural aggregate is the residual cement mortar that remains attached to the RA surface. This attached mortar leads to inherent defects in RA, including high porosity, high water absorption, and a weakened interface. These defects can adversely affect the performance of recycled aggregate concrete (RAC), influencing its compatibility, mechanical properties, and durability in fresh mixtures 68 (and see more details in the SI section 3.10).

4) in line 50, billion tons (Gt, Gigaton) may be better as billion tons (Gt).

Response:

Thank you, we have adjusted accordingly.

5) Around 1.1 trillion tons of non-metallic minerals was extracted globally for construction between 1970 and 2019. This is equivalent to removing a 3–4-millimeter layer over the Earth's entire land surface (see Supplementary Notes for calculation). Is there any reference for this?

Response:

Thank you for the question. As it is hard to imagine 1.1 trillion tons we calculate this thickness ourselves to offer a different perspective. The calculation is included in the the Supplementary Notes line 1083.

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.

6) In recent years, China has historically consumed around half of global aggregates extracted. what does this mean? China consumed around half of global aggregates extracted historically, or only in recent years?

Response:

Thank you for raising this point. The statement refers to recent years, particularly after 2010. We will clarify this in the main text:

Line 54: In recent years, particularly after 2010, China has consumed around half of the global aggregates extracted.

7)Building one square meter of a building requires 1.2 tons. This sentence needs to be revised to make it clear.

Response:

Thank you and we adjusted to:

Line 56: Constructing one square meter of a building requires 1.2 tons of aggregates.

8) in line 63, concrete-based construction has led to enormous demand for aggregates, for should be of.

Response:

Thank you we have corrected this.

9) in line 66, at a local level, what is a local level? provincial level or village level?

Response:

Thank you for the question. By "local level," we refer to subnational levels, and ideally, finer scales such as village or municipal levels. However, due to the scope of this study and data availability, we focus on the provincial level in this paper. We have updated the sentence to read:

Line 65: Globally, there is little risk of exhausting these resources, however, high transport costs and rising local prices can limit demand. A 50-150 km radius6,7 is typically the limit for local resource extraction and utilization. Thus, local analyses at finer scales, including down to the municipal level 1,8 are vital for addressing these specific challenges.

10) is sand really common pool resource?

Response:

Thank you for your question. This perspective is drawn from this article (https://www.science.org/doi/10.1126/science.aao0503).

From an economic standpoint, a common-pool resource has two key characteristics: difficulty in excluding users and subtractability, meaning one person's use reduces availability for others. In many regions, sand meets these criteria. It can be extracted from riverbeds, coastlines, or quarries, where property rights enforcement is often weak. In such areas, unregulated extraction leads to competitive consumption. As more sand is mined, less remains available for others, creating conflicts among users.

However, in contexts with stricter regulations or well-defined ownership, classifying sand as a common-pool resource may differ. Some governments issue sand mining permits, regulate beach extractions, or impose restrictions on supply chains. These measures can shift sand from an open-access resource to a more controlled commodity. Nevertheless, in areas lacking strong regulation, sand extraction remains susceptible to overuse in the absence of collective management approaches.

11) the introduction maybe too long, it would be good to make it concise.

Response:

Thank you very much. We have made some edits while preserving the original meaning.

12) the maps lacks basic component, like the scale bar and the north arrow, for example, figure 4.

Response:

Thank you very much. Following your suggestion, we have made the revisions and added a scale bar and a north arrow to the figure.

Reviewer #1 (Remarks on code availability):The code can be used and the results of the paper are reproducible.

Response:

Again, we sincerely appreciate your positive feedback and insightful recommendations. These have greatly contributed to improving our manuscript.

Response to Reviewer #2:

General : I have four main concerns, some of them developed in the two following sections.

I) Many studies embrace a similar approach to this study (e.g. 86 studies of road MFA reviewed in this paper, including several prospective studies, and even changes due to climate damage: https://www.sciencedirect.com/science/article/pii/S0921344924001782?via%3Dihub). What is the specific originality of this model/study?

Response:

Thank you for your thoughtful comments and feedback. We have carefully revised the manuscript based on your points.

(1) Model development. We designed a dynamic social metabolism model that tracks aggregate flows from extraction through end uses, explicitly integrating circular economy measures and incorporating scenario analyses using Shared Socioeconomic Pathways (SSPs). Although Material Flow Analysis (MFA) is well established, **our study provides clear novelty by conducting future scenario analyses for China—a key knowledge gap that has not been addressed in previous research**.

(2) Data Refinement. We compiled thousands of input parameters (e.g., intensity coefficients, lifespan data, scenario assumptions) and validated them through consultations with the China Aggregates Association and other stakeholders. **This extensive dataset offers granular insights that go beyond typical simplified approaches, improving the model's reliability and depth**.

(3) Extended Scope. **Our analysis covers 31 provinces from 1978 to 2050, incorporating subnational variations that have not been systematically reported in prior research**. We also assess future pathways under circular-economy-oriented scenarios. These dimensions—spatial detail, temporal depth, and forward-looking strategies—underscore the study's originality and relevance.

Following your suggestion, we have updated the paragraph in the Introduction as follows:

Line 114: To address these gaps, we developed the China Aggregate Metabolism Provincial Scenarios (CHAMPS) model (Figures S3–5), a dynamic scenario-based metabolism framework for aggregate resources that tracks material flows across 31 provinces in mainland China from 1978 to 2050 (see Figure S2). CHAMPS provides a comprehensive view of aggregate supply and usage, mapping processing stages to end uses for 30 distinct end uses grouped into eight categories, while integrating circular economy measures with SSP-based socioeconomic data to project future scenarios.

We assembled a comprehensive dataset of thousands of input parameters, validated through stakeholder consultations, thereby achieving the highest possible level of granularity for China's aggregate sector. Our projections extend to 2050 under six scenarios and explore effective circular economy approaches.

We begin with a Baseline (BL) scenario reflecting China's current state and future path (based on Shared Socioeconomic Pathway 239, SSP2). Building on this, we then assess four strategies—Intensive Use (IU), Lightweight Design (LD), Lifetime Extension (LE), and Improved Recycling (IR)—plus an integrated All Measures (AM) approach. These strategies incorporate 3R (Reduce, Reuse, Recycle) principles40 to enhance sustainability (see Table 1 and Supplemental Notes 2.4). By filling a knowledge gap in China's aggregate demand and supply dynamics, we hope to contribute broader discussions on sustainable resource management in developing regions and offer a fresh perspective on achieving more efficient resource use while mitigating environmental impacts.

II) Reproducibility of the study is ensured thanks to the open-source code. But transparence of the study is not at the level expected in a Nature Portfolio journal. Especially, references to justify parameters' values (recycling rates, lifespans, material intensities) are not clear.

Response:

Thank you very much for your suggestion regarding data sources. Following your advice, we have now explicitly added the relevant references in Section 1.2 and provided illustrative examples in Table S11, ensuring that readers can easily verify each data point. Please review Section 1.2 and Table S11.

III) Input parameter values such as infrastructure lifespans and material intensity are crucial to the robustness of the output. How certain are these values? The +/-10% uncertainty propagation shows a linearity of the outputs to the inputs, and +/-10% uncertainty of the inputs may be highly underestimated.

Response:

Thank you for highlighting this important issue. We agree that a fixed ±10% uncertainty range may underestimate variability in key parameters such as infrastructure lifespans and material intensities. In response, we refined our Monte Carlo analysis, drawing on the approach in Krausmann et al. 2017 (https://www.pnas.org/doi/10.1073/pnas.1613773114), and assigned parameter-specific uncertainty ranges that more accurately capture China's conditions. Details on these revised uncertainty levels and their impacts are provided in Tables S15 and S16:

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

	Material 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 Gravel 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%

[1] Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, Fishman T, et al. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc Natl Acad Sci U S A. 2017;114(8):1880-5.

IV) How certain the authors are about the substitutability rate of natural aggregates by recycled aggregates (e.g. data in Figure S3)? Downcycling is currently the norm, for many reasons (quality issues, recycling operation complexity, cost, etc.). Little references and justifications are given on the values chosen, while this part of the modeling leads to one of the key messages of the paper. The manuscript needs to strongly support the assumptions taken on that side.

Response:

Thank you for your question. To give further details.

In this study, the historical recycling rates were derived from relevant reports and literature (https://www.ndrc.gov.cn/xwdt/xwfb/201410/W020190905399746121257.pdf; https://www.gov.cn/xinwen/2021-12/09/content_5659650.htm; http://www.chinajsb.cn/html/202004/08/9222.html; https://www.sciencedirect.com/science/article/abs/pii/S0921344917303142) and corroborated by expert consultations. In the scenario analysis, the baseline scenario was set by referencing the recycling rate from 2020—the final year covered in the retrospective study—as detailed in Section 2.3 of the SI notes. We have added a citation to the references in the Supply Side section of the main text's Scenario Settings, and a detailed description is also provided in section 2.3 of the SI NOTES:

> *Line 747: Under the baseline scenario, the recycling and downcycling rates for aggregate waste from various end uses are benchmarked against the prevailing conditions7,42-45 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.*

Regarding the recycling and downcycling, in Section 2.3 of our SI notes, we distinguish between recycling and downcycling based on data from the National Development and Reform Commission of China (https://www.ndrc.gov.cn/xwdt/xwfb/201410/W020190905399746121257.pdf).

Specifically, for construction and demolition waste (CDW) generated by building demolition, only a portion is recycled back into building materials, while the remainder undergoes downcycling. For the improved recycling scenario, both the recycling rates and substitution ratios draw on current rates in developed countries and the technical constraints of recycled aggregates (https://link.springer.com/article/10.1007/s11356-024-32397-9).

In many European and North American nations, the recycling rate of CDW can reach 70–90%, whereas China's rate is generally estimated below 10–20% (https://link.springer.com/article/10.1007/s11356-024-32397-9; http://www.chinajsb.cn/html/202004/08/9222.html; https://www.gov.cn/xinwen/2021-12/09/content_5659650.htm). From a technological perspective, Harish et al. (https://link.springer.com/article/10.1007/s40996-024-01539-x) report that a 25% recycled aggregate (RA) replacement ratio in concrete achieves optimal performance, whereas higher ratios degrade properties. Ongoing advancements in RA separation techniques and high-performance superplasticizers may, however, allow for greater RA substitution in the future.

In our improved recycling scenario, by 2050, around 30% of building-derived aggregate waste is recycled in building construction. At that time, aggregate demand approximately matches waste generation, so the substitution rate also reaches about 30%, remaining technically viable. Additionally, we assume that 20% of construction-related sand and gravel waste is recycled for infrastructure, such as concrete blocks for road paving; 30% is downcycled to fillings; and the remaining 20% is disposed of in landfills. For the baseline scenario, we consider 4.8% recycled for buildings, 3.2% recycled for infrastructure, 9.2% downcycled to fillings, and 82.8% disposed of in landfills.

Detailed annual recycling rates for this scenario are documented in our "*Supplementary_Dataset_Underlying data & Parameters.xlsx*."

We have added clarifications in the SI (section 3.10) and provided a concise explanation in the main text:

> *Line 130: Downcycling and recycling are explicitly included in our modelling, for further details please see Supplemental Notes Section 2.3.*
>
> *Line 377: From a technical perspective, the key difference between recycled aggregates (RA) and primary aggregates is the residual cement mortar that remains attached to the RA surface. This attached mortar leads to inherent defects in RA, including high porosity, high water absorption, and a weakened interface. These defects can adversely affect the performance of recycled aggregate concrete (RAC), influencing its compatibility, mechanical properties, and durability in fresh mixtures 69 (and see more details in the SI section 3.10).*

Former comments:

(1) Thank you to the authors for recapping the main lines of their model. What is included in MF3, and how the energy transition, and, more importantly, climate change damage could impact the robustness of the model (e.g., increase need in maintenance/reconstruction of the structures)? The energy sector may require more concrete with the deployment of renewable energy infrastructure, while climate change

will have an impact on the lifespan of the structures and the consumption of sand and gravel. If the authors consider SSP2 as the societal narrative, there is little chance to respect the Paris agreement, and we may head to +2.7-+3.1°C by the end of the century compared to re-industrial temperatures, what would have strong impacts in terms of infrastructure damage and aggregate consumption even by 2050.

Response:

Thank you for your valuable comments and questions.

As shown in Figure S3 in SI, MF3 includes the inflow and outflow of stocks for various end uses. This represents how aggregates are incorporated into infrastructure and buildings and later removed as waste or recycled when these structures reach the end of their life.

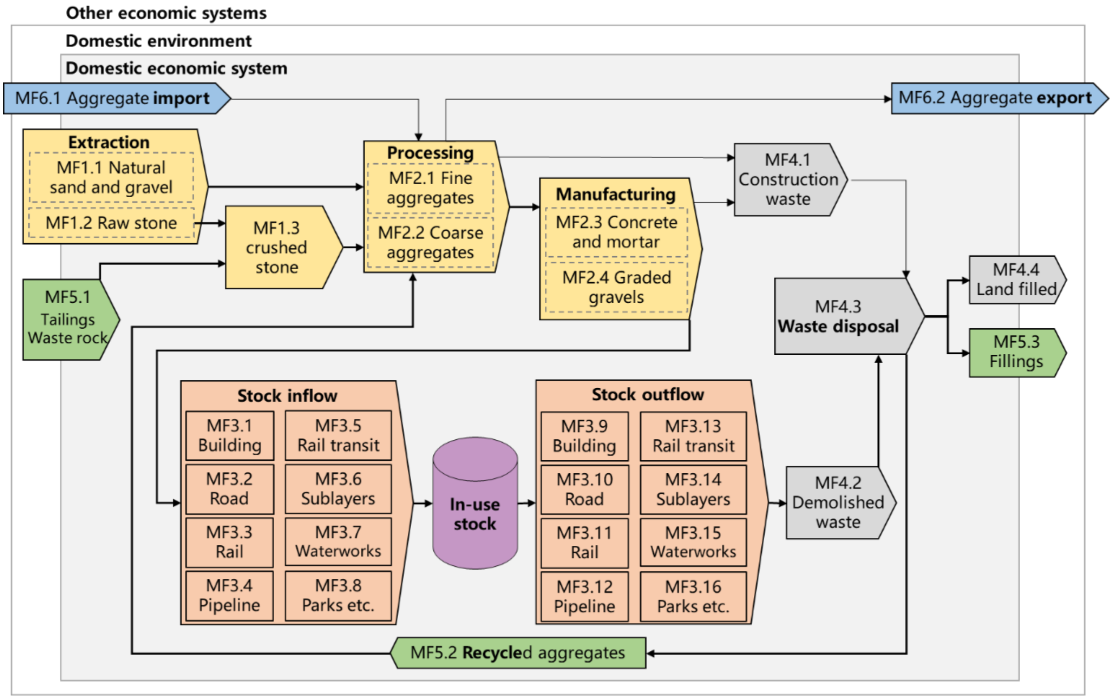

Figure S3 Aggregate metabolism model.

Regarding the potential impacts of the energy transition and climate change on aggregate demand, we believe these factors have limited influence. Our analysis and existing studies indicate that aggregate demand is predominantly driven by traditional infrastructure and housing construction (https://www.sciencedirect.com/science/article/pii/S0921344922000210; https://www.nature.com/articles/s41893-022-00857-0; https://www.nature.com/articles/s41467-021-25300-4), which are closely linked to population growth and conventional infrastructure/building needs. In contrast, the material requirements for the energy transition, such as renewable energy infrastructure, are largely metal-based (https://www.sciencedirect.com/science/article/pii/S2590332221001214). Therefore, we expect minimal changes in aggregate demand from this aspect. While higher temperatures and extreme weather events could affect the lifespan and maintenance of structures, leading to changes in aggregate consumption, these impacts remain uncertain and were not explicitly modeled in this study. Thank you for the good point. This could be an area for future research.

We selected SSP2 because it assumes a "middle of the road" socio-economic pathway, which is neither overly optimistic nor particularly challenging. This narrative closely reflects current global trends and provides a stable basis for analyzing the impacts of circular economy policies and technological changes (https://www.sciencedirect.com/science/article/pii/S2590332221001214). This approach is a common practice in material flow scenario studies (https://www.nature.com/articles/s41467-021-25300-4; https://www.nature.com/articles/s41558-023-01782-6).

We agree that the relationship between SSP2 and temperature increases above the Paris Agreement targets is an interesting topic for future research. However, this falls outside the scope of the current study, which focuses primarily on material flows. The choice of SSP2 aligns with common practices in material flow scenario research, and we look forward to exploring this aspect in future work. Thank you for your great comment!

(2) (3) Thank you for the author's clarifications. The title only mentions sand, while sand and gravel – i.e., aggregates according to the author's definitions - are covered by the model. I still believe the title should be modified, because "sand" does not reflect the studied object, and sand has a specific history of scientific publication with specific stakes that are not the main point of this publication. Moreover, I believe sand is a much smaller share of total aggregates in volume/weight than other types of aggregates. So using sand gives a distorted view of the content of the article.

Response:

Thank you for your suggestion. Following your suggestion, we revised the title to:

The Future of Sand, Gravel and Crushed Stone in China: Declining Demand and Circular Transition Possibilities.

(3) I have serious doubts on the reliability of the average lifetimes considered, and I question the values of the material intensity chosen too.

a. First, are the sources in column 6 of table S11 for lifespans, numbers of unit of each category of stock, and material intensities, or only lifespans? We need to follow the sources for each category of value, otherwise the study is not transparent.

Response:

Thank you for your comment. We confirm that the references in column 6 of Table S11 cover all relevant data sources, including those for lifespans, stock classifications, and material intensities. Most information was extracted from publicly available yearbooks and databases issued by the National Bureau of Statistics of China, although certain materials require institutional access (e.g., through Tsinghua University's library).

Material intensities primarily derive from peer-reviewed literature and industry reports (e.g., those by the China Aggregates Association), while lifespans rely on published studies and, where applicable, official standards (such as those regulating road infrastructure). These sources are detailed in the Table S11 Supplementary Information.

Recognizing that some Chinese databases may be less accessible to international researchers, we have specified in the Data Availability section that any additional requests can be directed to the lead contact. We are happy to provide further assistance as needed to maintain transparency and reproducibility.

b. Secondly, when I check some of the references given, it is hard, sometimes impossible, to find the data and assess its robustness. For instance: Reference [51] "National Bureau of Statistics of China. *National Data*, 266 <http://www.stats.gov.cn/english/ (accessed Nov 26, 2023)> (1949-2022)" is a source for the values of buildings, roads, railways... but the link brings to a general request webpage, and typing "building lifespan" does not provide any document/data. Please be more specific in the author's references to be fully transparent. Same for all the references to Chinese yearbooks/statistics (e.g., [60]-[63]): where exactly can we find the values? Is there a name of chapter/specific dataset the authors use? Reference [52] : the material flows evaluated are for construction and demolition only, not maintenance. It means that if material intensity are derived from this study, it is underestimated compared to a full life cycle approach where inflows must consider construction/maintenance/reconstruction to be complete. Reference [53]: an average lifespan of 30 and 20 years is indeed considered in this study for urban and rural residential buildings, but [53] is not the source of these values: it quotes Song 2004 and the Center for Housing Industrialization 2011. None of the study is accessible to me so I cannot check the quality of these estimates. + Please always cite the original study/ies, not derived studies using the values from the original studies.

Response:

Thank you for your detailed comments. We understand and agree with your suggestions regarding data transparency, and we have provided clarifications below.

In this study, the underlying data regarding the final usage of various aggregate resources are mainly sourced from the Chinese National Bureau of Statistics, including indicators such as building floor area and road mileage. The building lifespan data are referenced from relevant literature (e.g., https://link.springer.com/article/10.1007/s11625-012-0196-y; https://www.sciencedirect.com/science/article/abs/pii/S0921344912002273).

The life expectations for roads and railways are based on standards and additional literature (e.g., https://xxgk.mot.gov.cn/2020/jigou/glj/202006/t20200623_3312197.html; https://www.nra.gov.cn/xxgk/gkml/ztjg/bzgf/jsbz/201701/t20170103_319456.shtml; https://link.springer.com/article/10.1007/s11625-012-0196-y) and Chinese standards, such as the *Technical Standard of Highway Engineering* (JTG B01-2014), which is available only in Chinese. All the relevant references have been duly cited and labeled in Figure S11.

Additionally, we have provided a screenshot from the National Bureau of Statistics website, which outlines the underlying data used:

[Figure Redacted]

References [60]-[63] (now references [22][19][89][90] in the SI) correspond to official Chinese yearbooks, which are publicly available but do not have English versions and often require paid access. The English names in the references are translations of these yearbooks. In our research, we accessed these yearbooks through institutional databases such as CNKI and EPS.

Regarding Reference [52] (now [87] in the SI), while its title suggests a focus on construction and demolition, it covers the entire process, including both CDW generated during renovation and that from demolition. Our material flow model considers the entire life cycle of aggregates, from extraction and processing to construction, use, and eventual demolition or recycling. Additionally, our dynamic material flow model accounts for stock metabolism over time, ensuring a comprehensive approach. The inclusion of the full life cycle is separate from the determination of material intensity values, which were derived from multiple sources.

For Reference [53] (now [30] in the SI), we appreciate your suggestion, and we improved the citations to include the original studies, including Song (2004) and the Center for Housing Industrialization (2011).

We understand the importance of citing primary sources to ensure transparency and traceability of the data. We acknowledge that these platforms may not be easily accessible to international scholars, as specific links often lead only to a general request webpage. To address this, we have noted in the Data Availability section that further requests for resources can be directed to, and will be fulfilled by, the lead contact. We are happy to provide additional assistance to ensure accessibility.

i. Type of data and quality: to perform uncertainty propragation, the Pedigree Matrix approach gives a classification of the quality of the data depending on how it was produced. For instance, in terms of completeness, using statistical data for the China is the best approach for lifespans and material intensities, rather than using single values/expert estimates. If some data are theoretical (such as lifespans from construction codes/standard for instance), they are highly uncertain, conclusions are not robust, and recommendations should not be emitted. Could the authors qualify the quality of their main parameters' values (e.g. lifespans and material intensities) using for instance the Pedigree Matrix approach?

Response:

Thank you for this. Based on your suggestions, we have revised the Monte Carlo analysis. Specifically, we referred to Krausmann, Fridolin, et al., (https://www.pnas.org/doi/10.1073/pnas.1613773114). Incorporating China's specific context, we assigned uncertainty to different original input data. For the statistical data we obtained, we assumed high reliability and, therefore, did not assign any uncertainty. The uncertainties of the input parameters are detailed in Table S15.

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

	Material 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%

[1] Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, Fishman T, et al. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc Natl Acad Sci U S A. 2017;114(8):1880-5.

ii. Especially, I find lifespans quite short for: building in general (and especially residential buildings, plus there is an inconsistency: in Table S11 for residential buildings, values between 25-35 years are considered while authors have stated elsewhere in the text "The service lifespan of residential buildings in China has traditionally been much shorter than that in developed economies, typically ranging from 30 to 40 years.") and roads (many construction standard outside of China consider lifespans of 20 and 30 years, resp. for secondary and main roads. And the real lifespans exceed most of the time the theoretical lifespan). Moreover, for roads, different layers of the infrastructure have different lifespans, superficial layers having globally much shorter lifespans than deeper layers. Does the model consider a weighed lifespan average over the different layers, depending on the category of roads and their thickness per layer? It would change a lot the quantity of aggregates consumed overtime to have this type of realistic approach. For ballast-based railroads, it also has different layers of materials (ballast, blankets and subgrades) with different lifetimes. Maintenance of the ballast includes over the lifetime of the infrastructure refilling, partial changes, and finally a complete change, each of these activities generating input and output flows. The author's can find an example of a maintenance plan in the section 2.4.6 of this article : https://link.springer.com/article/10.1007/s11367-019-01727-2. For a concrete bed railway, the lifetime will also be different. What kind of railways are built in China and how these different lifespans have been considered in the model?

Response:

Thank you for your detailed comments. We have addressed your concerns as follows:

For residential buildings, the expected lifespan of 35 years applies to those constructed after 2000, aligning with the 30–40 years stated in the text. The 25-year lifespan reflects buildings constructed prior to China's economic reforms (1978), during a time of significant economic challenges and limited resources. The shorter lifespans of these older buildings are consistent with the historical context and construction standards of that period (https://www.tandfonline.com/doi/full/10.1080/09613211003729988). We cite this in the supplementary information.

For roads, we based our lifespan estimates on national standards. The sources are cited in Supplemental Notes [23-25]:

- Ministry of Transport of China. Specifications for Design of Highway Subgrades. (2015).

- Ministry of Transport of China. Technical Standard of Highway Engineering. Vol. JTG B01-2014 (China Communication Press, 2015).

- Ministry of Transport of the People's Republic of China. Vol. JTG B01—2014 (ed Ministry of Transport of the People's Republic of China) (China Communications Press, Beijing, 2015).

We agree with your observation to consider different layers of road infrastructure. In our model, roads are divided into surface and base layers, with separate coefficients provided in the dataset included in the Supplementary Notes. The lifespan of surface layers follows China's standard, while base layers are assigned a lifespan of 80 years, referencing the durability of building foundations (https://www.pnas.org/doi/10.1073/pnas.1613773114).

Other additional points including The relatively short lifespan of roads, from a dynamic material flow perspective, can be attributed to several factors: 1) The rapid development phase in China has led to a focus on fast construction, often at the cost of lower quality (https://onlinelibrary.wiley.com/doi/full/10.1111/grow.12617); 2) The large population and high traffic density in China contribute to significant road damage (https://www.sciencedirect.com/science/article/abs/pii/S0022437510000083); 3) The prevalence of heavy trucks in China, which is less common in developed countries, places additional stress on road infrastructure (https://onlinelibrary.wiley.com/doi/full/10.1155/2021/9998405). The following video provides further explanation: https://www.youtube.com/watch?v=RFB1KprqDTU

For railroads, while they are also composed of multiple layers, we did not adopt the same level of categorization as for roads due to data limitations. In China, it is challenging to obtain consistent and detailed classifications of ballast-based versus concrete-bed railways. Additionally, geological conditions vary significantly, with some regions requiring extensive subgrade preparation and others requiring minimal groundwork. As such, we categorized railroads into ordinary rail and high-speed rail without further differentiation of surface and base layers.

Railroads contribute less than 5% of the total aggregate flows and stocks in China. Given their relatively minor impact, adopting a simplified approach is reasonable in this context. We appreciate the reference you provided and have reviewed and cited it in the revised manuscript. The article provides a detailed analysis of the environmental impacts of different components of high-speed rail, which is based on an LCA (Life Cycle Assessment) framework. While LCA focuses on environmental impacts, it differs conceptually from resource quantification. We have included a discussion of this reference in the future outlook section.

Please explain how the authors consider these different lifespans for the different parts of the road and rail infrastructure, as a fine modeling is crucial to the estimated input and output aggregate flows in the model. The authors need to explicit better what are the data considered for the material intensity of the infrastructure. Are they values on the entire life cycle, or just for the construction, without the maintenance? I know the authors provide their code, but it is not self explanatory, and the model must be explicated finely enough in the SI.

Response:

Thank you for your question. We supplement the SI with additional details on the model and data to ensure clarity.

For the material intensity of infrastructure, we derived the coefficients through a combination of sources, including articles from the China Aggregates Association and collaborative estimations with their experts. Specifically, these estimations are based on standard construction specifications. We calculated the thickness and average width of various road layers and then multiplied these by the density of concrete or aggregates to derive the material intensities. Further details are provided in SI Section 1.2. Additionally, the SI parameter Excel file includes a layer-by-layer breakdown for the roads, containing comprehensive raw data.

For example, our supporting data Excel file includes:

Table (Extracted from the SI parameter Excel file) The strength of the gravel materials in the surface and base layers of the primary and secondary highways in Beijing in 2020.

Province	Year	Final use	Material	Material intensity	Unit	Model
Beijing	2020	1st-class highway surface layer	aggregates	8960.00	t/km	stock-driven
Beijing	2020	2nd-class highway surface layer	aggregates	2800.00	t/km	stock-driven
Beijing	2020	1st-class highway sublayer	aggregates	17920.00	t/km	stock-driven
Beijing	2020	2nd-class highway sublayer	aggregates	5600.00	t/km	stock-driven

Table (Extracted from the SI parameter Excel file) The expected lifespan of the surface and base layers of the primary and secondary highways in China in 2020.

Year	Final use	Lifetime expectation
2020	1st-class highway surface layer	12
2020	2nd-class highway surface layer	10
2020	road sublayer	80

Additionally, we employed a dynamic material flow model, which inherently accounts for the gradual metabolism of stocks during their use phase. Within our broader material flow framework, we also consider the full life cycle flows of aggregates within the economic system, from extraction and processing to construction, maintenance, and eventual demolition or recycling.

It is important to note that, as with all macro-scale research, precise calculations are inherently challenging. However, we believe our study achieves a high degree of accuracy, leveraging the best available data and methods to provide robust and meaningful insights.

(5) (6) About the uncertainty analysis conducted: the authors conduct a Monte Carlo analysis with a +/- 10 % normal distribution range with 1000 runs. First, how a +/- 10 % normal distribution range can be proven as realistic/representative of the natural variability of the input values? It seems absolutely too low to me. Secondly, 1000 runs is a default value but is low (see http://link.springer.com/10.1007/s11367-019-01698-4). How these choices affect the result of the Monte Carlo simulation? Last, the analysis shows a linearity of the output uncertainty to the input uncertainty. The question of quality of input data addressed above is thus crucial to be addressed.

+ I think this part of the manuscript needs to be rephrased: “"a Monte Carlo simulation method across 1000 iterations, allowing parameter fluctuations within a ±10% normal distribution range, achieving 99.5% confidence.". It is unclear, and normal distributions have two parameters: the mean and the variance. +/-10% would be rather given for a uniform distribution.

Response:

Thank you for these suggestions. We have now added uncertainty ratings for each input parameter that can range beyond +/-10%. (see Table S15).

Second, we increased the number of iterations in the Monte Carlo simulation to 10,000.

Lastly, we revised the description of the uncertainty analysis in the manuscript for clarity in both manuscript and SI.

The manuscript text now reads:

Line 629: To assess the impact of these uncertainties on model outcomes, a Monte Carlo simulation was used 92,93 with 10,000 iterations and normally distributed parameter variations weighted according to the data availability and precision of each variable (see Table S15) at a 95.5% confidence level. This analysis focused on the model's core—dynamic material flow analysis—particularly its stock linkage. The other parts of the model based on conservation of mass indicate a strong linear correlation between parameter variations and model outputs so it is not necessary to include a further uncertainty analysis in other model segments. The simulation validated the core model's reliability, with results (Supplementary Figures S28-S33) showing most variations stay within ±30.9% of inflows, ±16.9% of stocks, and ±49.9% of outflows across provinces.

In SI, it now reads:

Line 650: 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%. 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 literature1 and considered factors such as the availability of China's underlying data on gravel 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 practice1.

As shown in Figures S28-S33, the results of the Monte Carlo simulations for Beijing are displayed. All 10,000 results were plotted on the results graph. It is clear that the differences between the maximum and minimum data points for each year are acceptable, generally staying within ±30.9% of inflows, ±16.9% of stocks, and ±49.9% of outflows across provinces. For major aggregate end uses such as housing and roads, only slight variations were observed and showed close agreement. The simulation validated the core model's reliability, with results (Supplementary Figures S28-S33) showing most variations staying within ±30.9% of inflows, ±16.9% of stocks, and ±49.9% of outflows across provinces.

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 gravel demand in most provinces is within 25%, the maximum deviation of gravel stocks is generally within 12%, and the maximum deviation of gravel 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.

(7) the additions to the conclusions are to my point of view still very general, similar to what has already been published in the past, and not specific enough to the model done. The transition from the object of the model – aggregates – to the specific sand crisis is, to my point of view, clumsy.

Response:

We appreciate the reviewer's feedback. We have revised the discussion further.

Below is a summary of the novel key points discussed in the revised manuscript:

(1) Novel findings from this model :

- Our study indicates that aggregate demand is expected to decline post-2020 due to market saturation. By 2030, demand may stabilize at half the 2020 level.

- Historically high demand in affluent coastal regions is nearing saturation, while inland regions, though with lower demand, are also approaching peak levels. Given these differences, caution is needed regarding potential overcapacity as demand declines.

(2) Challenges and Importance of Recycled Aggregates: We discuss the importance of recycled aggregates from both technical and market perspectives.

(3) Global Relevance of the Chinese Model:

- Extending the findings of the Chinese model, we project that by 2030, China will increase its use of recycled aggregates, reducing the demand for natural sand, gravel, and crushed stone. However, global aggregate demand is expected to peak between 2060-2070, after which China may no longer be the leading consumer, especially with China's demographics.

- It is essential to assess the evolving urban development and sustainable aggregate demand in emerging markets such as the Middle East, Africa, South Asia, and South America, which may become the primary markets for aggregates.

(4) Future Integration of MFA, LCA, and GIS: We discuss the potential integration of material flow analysis (MFA) models, such as CHAMPS, with life cycle assessment (LCA) and Geographic Information Systems (GIS) to explore more specific impacts and regional sand and gravel recycling planning.

(5) Tailings as a Source and Environmental Challenges: We discuss the environmental challenges of tailings management, noting that these issues require further investigation.

(6) Local Nature of the Sand Crisis and conclusion: We emphasize that the sand crisis is not a global issue but a localized one. Oversimplifying the crisis may overlook critical political, economic, environmental, and social dynamics. Based on our findings, we conclude that strong, evidence-based policy support and local supply-demand planning are crucial for addressing the sustainability challenges of sand and gravel, particularly in rapidly developing economies.

Additional points

a) The information conveyed in table S11 would me more interesting for entire China than for Beijing to give an overview of the infrastructure stock, and lifespans / material intensity intervals in the country.

Response:

Thank you for your suggestion. We have mainly revised the presentation format of data sources in Table S11. This table serves as supplementary material for data sources, using Beijing as a case. Given that the national data spans 31 provinces over a long time period, creating an overview might be overly extensive and complex. Following your suggestion, we added a summary table (Table S12). The complete data is included in the Supplementary_Dataset_Parameters.xlsx file, where the readers can find the most detailed and underlying information.

b) Figure S4 : I don't understand the color code. Why 10 boxes are represented for the final uses, but the text says "8 category, 30 sub-category": it does not match (+ typos) + the "lifetime distribution" curve and box make think that probability distributions are considered for lifespan values, while according to the table the authors shared in their rebuttals, average lifespans seem to be considered by type of infrastructure and region.

Response:

Thank you for these points. The discrepancies in the categories arise because residential, non-residential, and rural buildings are all grouped under the broader category of "building foundations (non-groundwork)." We have added a note below the figure to clarify this classification.

The color codes in the figure represent different driving factors: red indicates stock-driven uses, while blue represents flow-driven uses, corresponding to our modeling approach.

Regarding the "lifetime distribution" curve, the lifespans of individual end uses are indeed modeled as distributions rather than fixed values. For example, if the average lifespan of a particular batch of buildings is 40 years, some buildings may be demolished after 38 years, while others might last up to 45 years. However, these variations are modeled to converge around the average value, aligning with real-world dynamics. We have updated Figure S4 which now is shown as:

[Figure Redacted]

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 dy-MFA, and blue indicates inflow-driven dy-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.

c) Why are there 8 categories / 10 categories of final uses according to figure S4, 17 final uses in the projection on demand side in Figure S5, and 9 final uses in Figure S8? This illustrates why the methodology is hard to follow.

Response:

In the historical analysis, we initially used 8 major categories and 30 subcategories to classify final uses. For the projection of future scenarios, these 30 subcategories were consolidated into 17 subcategories to simplify the analysis and focus on key trends. In Figure S8, some of the boxes represent multiple subcategories, which are clarified in the figure notes.

Following your suggestion, we have now clearly outlined the classification of the 8 major categories in Section 1.1.1 of the SI and added specific notes in the figure captions to help readers better follow the methodology.

d) Recycling rates, as well as all parameter's values, need to be supported more strongly. Little references are given. For instance, all the figures from Tables S3 and S4 need to be understandable for the readers. Where do they come from? E.g. "According to the "China Resource Comprehensive Utilization Annual Report" and expert consultations, the utilization rates of aggregate waste": no reference to the report, what kinds of experts?. Another example "Under the baseline scenario, the recycling and downcycling rates for aggregate waste from various end uses are benchmarked against the prevailing conditions in 2020, as follows:": no reference is given.

Response:

We acknowledge the importance of providing clear references and supporting information for parameters such as recycling rates. Recycling rate data are inherently scarce, and we have utilized all accessible resources for this study. Additionally, we conducted extensive consultations and validations with experts from the China Aggregates Association and Beijing University of Civil Engineering and Architecture. One of the co-authors, Professor Fei Li, specializes in the resource utilization of construction waste, high-performance concrete and its raw materials (aggregates), and recycled aggregate technologies. His expertise provided valuable industry insights and guidance for this study. Relevant published reports have been cited in the SI: http://www.chinajsb.cn/html/202004/08/9222.html; http://sthjj.nc.gov.cn/ncgbj/hjxw/202009/1cc035bfe53c44398fd665106a5d55c8.shtml; https://www.gov.cn/xinwen/2021-12/09/content_5659650.htm).

For the 2020 baseline recycling rates, no official data was available. We derived these estimates based on data from existing reports and expert consultations. While this approach involves estimation, we believe it represents the most detailed and reliable method available to date. Given the current limitations in data availability, we are confident that our approach provides the best possible representation of the recycling rates.

e) No consideration on reducing the development of infrastructure has been done, while reducing end-use consumption is a key aspect of the transition.

Response:

Thank you for your comment. We have considered reducing end-use consumption in our analysis. This is reflected in the IU, LD, and LE scenarios, all of which incorporate measures to lower demand-side consumption.

f) Recycling may bring other environmental problems: energy consumption and others. Tailings request a lot of energy to be transformed in usable aggregates, leachate can contaminate the infrastructure environment in metals and increase toxicity. It would be wise to address in the conclusion potential burden-shiftings from some of the strategies proposed to the resource stake.

Response:

Thank you for your comment on the potential environmental trade-offs associated with recycling. In response, we have revised the discussion as follows:

Line 426: Additionally, ore-sand (from tailings and waste rock) is considered a subset of manufactured aggregates71. However, the share of ore-sand in *aggregate production in China remains relatively low (less than 2%), primarily due to concerns about pollution, excessive density, and the preference for prioritizing metal extraction from tailings. While the stockpile of tailings and waste rock in China has reached 60 billion tons72, which could potentially serve as an alternative source for natural aggregates, the energy consumption required to transform these materials into usable aggregates, as well as the risks of leachate contamination affecting infrastructure, must be carefully considered. Statistics and research on tailings ponds are generally lacking70, and whether or how to use these materials in a sustainable way still requires work. Future research can also assess any potential burden-shifting impacts from recycling strategies (see Supplemental Notes 3.9 for an extended discussion).*

(8) "Sand and gravel issues are often overlooked – in part because they are so abundant – ": overlooked by who? Not researchers at least considering the number of articles, and there are even articles for the public, and documentaries about the sand crisis.

Response:

Thank you for your comment. We agree with you that in recent years, there has been increasing attention to sand and gravel issues, as evidenced by a growing number of articles, documentaries, and public discussions, particularly after 2015. However, before this period, these issues were largely overlooked by various stakeholders, including the public, governments, and researchers. The scarcity of studies and policy discussions prior to 2015 reflects this historical lack of focus. Further, we would suggest that current articles and documentaries are only reaching a small subset of the public.

We have updated the sentence to imply that this overlooking of the issue has been historic.:

Line 74: Because of their perceived abundance, sand and gravel issues have historically been overlooked, degrading these common pool resources in many regions13. Some argue this trend has escalated into a sand (and gravel) crisis8,14-16.

(9) It is a general comment. The reader should not have to struggle to understand the sources of the values taken, and all the parameter's values need to be sourced in the method part.

Response:

Thank you. Those parameters are noted in the Supplemental Notes.

(18) "for most modern construction": contemporary would be better than modern maybe.

Response:

Thank you and we adjusted accordingly.

(21) “Supply-side changes are important and less environmentally impactful resources include crushed rocks from quarries (crushed stones or manufactured aggregates; see the definition in the Methods section), secondary aggregates from construction and demolition waste (CDW) and ore-sand (a by-product of mineral processing).”: this sustainability ranking is still dependent on the environmental indicators the author’s consider. I suggest the authors nuance “less environmentally impactful resources”.

Response:

Thank you, we have rephrased the statement.

> *Line 78: Supply-side changes will be important to addressing some of these problems. There are many investigations of alternative resources with potentially lower environmental impacts that include crushed rocks from quarries…*

(35) what are “the socioeconomic impacts of the COVID-19 pandemic”

Response:

Thank you for highlighting this. While COVID-19 has had some negative impacts on the economy, we have made some adjustments to make the statement more concise and clearer.

> *Line 143: This decrease is attributed to factors such as the slowdown in China’s construction industry42 and changing demographics43.*

(41) I would remove all the references to the “sand crisis” as the scope of the paper is broader as it deals with all the aggregates.

Response:

Thank you for your suggestion.

We understand the reasoning behind your preference regarding the term "crisis." In fact, many articles and reports discussing the "sand crisis" address both sand and gravel collectively, often using "sand" as a more concise term:

- Cao et al. Material efficiency to tackle the sand crisis. Nature Sustainability 5, 370-371, doi:10.1038/s41893-022-00869-w (2022).
- Zhong et al. Increasing material efficiencies of buildings to address the global sand crisis. Nature Sustainability 5, 389-392, doi:10.1038/s41893-022-00857-0 (2022).

- UNEP. Sand and sustainability: 10 strategic recommendations to avert a crisis. (United Nations Environment Programme, 2022).

The crisis itself arises from the insufficient availability of sand and gravel as aggregates, and sand is the component that most easily resonates with public perception. Thus, "sand" there can be seen as a generalized term for sand and gravel, emphasizing its natural attributes, while "aggregate" reflects its demand-driven characteristics.

The "sand crisis" is inherently part of aggregate research and falls within the broader concept of aggregates. For this reason, we believe retaining such references is appropriate. For instance, we have clarified this in the manuscript:

> *Some have suggested that this trend has worsened to the point that we now face a **sand (and gravel)** crisis.*

Once again, we sincerely thank you for your thoughtful comments and suggestions, which have been constructive in helping us refine and improve our manuscript.

Reviewer #2 (Remarks on code availability):

I have not been able to open the code (looping while downloading)

Response:

Thank you for highlighting this. We have uploaded our code the Code Ocean as recommended by the journal and hope this fixes the problem.

Response to Reviewer #4:

I (Reviewer 4) was thorough in my previous review. I thank the authors for their patience and for being thorough in their revision of the submitted manuscript and in their responses to my comments. The authors addressed my concerns, and their submitted manuscript is good; the limited number of minor comments below reflect that.

Response:

Thank you for your constructive comments and insightful suggestions. They have significantly strengthened our manuscript. We have carefully addressed each point raised and revised the manuscript accordingly.

Specific comments:

Line 469 Add a reference to support the statement, 'China's success in transitioning from natural to manufactured aggregates (crushed stone) through strong policy guidance demonstrates the effectiveness of targeted regulations in mitigating these impacts.'

Response:

Thank you. This sentence is merged with other part, and we added a reference there.

Line 77 Consider removing 'and', i.e., 'Supply-side changes are important. Less environmentally impactful resources include…', or similar restructuring.

Response:

Thank you and corrected.

Line 80 Consider reworking this sentence. I provide an example here of what I think might work better. 'However, [crushed rock] and [ore sand] are not without environmental impacts. Their use requires strict management, but their regulation is more feasible than that of [natural] sand and gravel, which are widely extracted illegally.'

Response:

Thank you so much! We adjusted it following your suggestion.

Line 169 '…coming future' □ '…near future.'

Response:

Thank you and we adjusted accordingly.

Line 341 '…under All Measure scenario,' □ 'under the All Measure scenario,'

Response:

Thank you and we adjusted accordingly.

Line 344 It might be worth adding a brief statement/caveat about the possibility/practicality of interregional redistribution of surplus waste aggregates.

Response:

Thank you for this great point. We have added sentences regarding this:

Line 337: Interregional redistribution of surplus waste aggregates is feasible but depends on transport infrastructure, costs, and policy enforcement. China's "shift from road to rail and water" policy59,60 and the Yangtze River's transport network61 support efficient redistribution. However, high transport costs, uneven logistics infrastructure, and local resistance may limit scalability.

Line 590 I think there is still something 'off' here, requiring a tweak.

(i) Would 'stocks [and] densities' rather than 'stocks or densities' be correct?

Response:

Thank you for pointing this out. We adjusted to make it clear:

Line 563: The methodology begins with calculating historical per capita stocks, and densities across diverse applications

(ii) Place the parentheses immediately after 'densities' as the examples relate to densities (demographics and factors influencing demographics) rather than stocks directly.

Response:

Thank you and we updated following your suggestion.

Line 670 Re my codebase comments: the authors explain, 'The core functionalities and models, including the CHAMPS model of one region, are fully implemented in the code we provided. The additional code for plotting and visualization, which can be quite complex and specific to our setup, is not included as it was deemed non-essential for replicating the model's results.' Thank you for clarifying. I also note that the Data Availability section explains that requests for resources will be fulfilled by the lead contact. Further requirements here are a decision for the journal.

Response:

Thank you for your comment.

Line 675 Remember to add the codebase information to the Code Availability section prior to publication.

Response:

Thank you for the kind reminder.

Reviewer #4 (Remarks on code availability): I have no additional comments. Whether the partial codebase is sufficient is at the discretion of the journal.

Response:

Again, we thank you for your encouraging comments and valuable suggestions. They have been instrumental in enhancing the quality of our manuscript.

Response to Reviewer #2:

(1) We thank the authors for the modifications done on the article. It has been significantly improved. Nevertheless, I believe it still needs to be enhanced to align with Nature portfolio's standard.

Part I - The text has improved, but to my opinion it is not finalized yet. The "main" particularly does still have structure flows, redundancy, and English clumsiness/vagueness.

For instance, there is a lot a redundancy along the text about the specification of some terms, and the text has to be cleaned to become fit and lean. I will just give a few examples but many can be found in the text:

For instance, p1l47: "sand, gravel, and stone. These substances, known as aggregates". Then, a second entire paragraph talks about aggregates (the term is used 4 times from p1l54-l60). Then paragraph 3, p1l62: "Aggregates (sand, gravel, and crushed stone) ».

Usage of brackets: it cuts the text, interrupt the reading flow, and can bring confusion, especially when not located at the end of a sentence. Example p1l76: "Some argue this trend has escalated into a sand (and gravel) crisis", p1l87 "holistic approach for addressing the sand (and gravel) crisis »: what does (and gravel" indicate? A lower level of alarm? Then write it clearly. As it is, it evocates the ideas of the authors are unclear.

Response:

Thank you for the feedback and comments. We have carefully revised the manuscript to streamline the structure, reduce redundancy, and improve clarity and the language. Specifically, we removed redundant explanations of aggregates and merged related descriptions to avoid repeated definitions across multiple paragraphs (e.g., P1 L47–L62).

Regarding the use of bracketed expressions, we initially used "Aggregates (sand, gravel, and crushed stone)" for the sake of precision. Many studies adopt inconsistent definitions of aggregates—some, for example, use "sand" to refer to various types of aggregates. In contrast, we aim for accuracy by explicitly including sand, gravel, and crushed stone. A more detailed discussion is provided in Supplementary Notes 3.1. Given this, we retain the full bracketed expression only at its first occurrence in the abstract, and use the term "aggregates" elsewhere for conciseness.

For instance, in the main text:

Aggregates are essential for most contemporary construction.

Here, we removed the bracketed expression following "Aggregates".

Similarly, the use of "sand (and gravel) crisis" was initially intended for rigor, as both sand and gravel are natural aggregates and share similar origins. However, we acknowledge that "sand crisis" has become a widely accepted expression and sufficiently conveys concerns about natural aggregate resources. Since the bracketed form may disrupt reading flow, we accept the reviewer's suggestion and have revised the phrase to "sand crisis."

For example, in the main text:

Some argue this trend has escalated into a sand crisis.

Here, we removed "(and gravel)" following "sand."

We have also reviewed other bracketed expressions in the manuscript and revised them where appropriate.

For example:

Many investigations explore alternative resources with potentially lower environmental impacts, including crushed rocks from quarries and secondary aggregates derived from construction and demolition waste (CDW) and ore-sand, a by-product of mineral processing.

In this sentence, we removed the bracketed explanation after "quarries" ("crushed stones or manufactured aggregates; see the definition in the Methods section").

In addition, we asked a native English-speaking co-author to carefully review the entire manuscript.

(2) P4l126 "(based on Shared Socioeconomic Pathway 240, SSP2)": the authors can just put SSP2 in brackets, and justify its used, like: based on Shared Socioeconomic Pathway 2 (SSP2) representing a middle of the road pathways40.

Response:

Thank you, we have corrected this and it now reads:

We begin with a Baseline (BL) scenario reflecting China's current state and future path based on Shared Socioeconomic Pathway 2 (SSP2) representing a middle of the road pathway.

(3) The use of the term "sustainability" in different places is very vague. What do the author refer to? Social, economic, or environmental sustainability? Triple bottom line sustainability?

Response:

Thank you for your suggestion. We have added specific details at each relevant point:

These strategies incorporate 3R (Reduce, Reuse, Recycle) principles to enhance sustainability ***of resource use and ecological environment*** *(see Table 1 and Supplemental Notes 2.4).*

Finally, we conclude that strong, evidence-based policy support and local supply-demand planning are essential to address sustainability challenges, ***including sand crisis and supply shortages of aggregate industry,*** *particularly in rapidly growing economies.*

(4) The manuscript includes a lot of “be verbs” that need to be avoided as much as possible in a scientific article. Some example, but please review your manuscript thoroughly:

P1L51: “That’s » (+ improper in an article)

“there is”, “is” “are”, “this is”

Response:

Thank you for pointing this out. We have reviewed the manuscript and revised a bit. In addition, we asked a native English-speaking co-author to carefully review the entire manuscript.

(5) Vital is repeated 9 times in the text.

Response:

Thank you—we have enhanced the diversity of expressions throughout the manuscript.

(6) **Part II -** In terms of scientific content and modeling:

In the end, the authors investigated a baseline scenario and then only scenarios focusing on solving the aggregate crisis. No pessimistic scenario was considered in terms of aggregate consumption, such as scenarios with higher growth rates and consumption increase. It is important to specify that in the text and potentially in the title

Response:

Thank you for your suggestion. We agree that scenario design is important, and we appreciate the opportunity to clarify our choice. In this study, we did not include pessimistic scenarios with higher aggregate consumption, as we consider such developments highly unlikely in the Chinese context. This is not only due to China’s demographic trajectory but also recent policies in the construction sector that increasingly prioritizes renovation over new construction — for example, through the promotion of urban regeneration and retrofitting of old residential communities. This shift aligns with the observed slowdown and even decline in total aggregate consumption since 2015.

Our baseline scenario follows the SSP2 pathway and reflects an empirically grounded trajectory. This is consistent with many previous studies, which also only focus on baseline and improvement scenarios. For example, Zhong et al. (https://www.nature.com/articles/s41893-022-00857-0) and Miller et al. (https://www.nature.com/articles/s41893-017-0009-5) developed multiple improvement scenarios but did not include pessimistic cases. China's current aggregate consumption—around 20 billion tons per year—is already exceptionally high, and projecting even greater levels would be bordering on unphysical.

More importantly, the messages we would like to convey are not on predicting total demand, but on evaluating how circular economy strategies could reshape the sector. For this purpose, the baseline scenario offers a conservative and suitable reference. That said, we agree that expanding the scenario space could be valuable, and we plan to explore this in future work.

We have added a short clarification in Supplementary Note 2.1.

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. 38, 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.

(7) P8l217: "Recycling of aggregate waste in China is expected to rise from 733.7 Mt in 2021 to 4.5 Gt": it would be interesting to understand a bit the concrete logistic changes needed for that (Need for new infrastructure? Any operational stake for decisionmakers?)

Response:

Thank you for this interesting suggestion. Indeed, a large-scale shift in aggregate demand and waste generation would require coordinated efforts to align supply chains, upgraded processing facilities, and improved transportation logistics. Policy support will also be essential, including tax incentives and subsidies for recycled aggregate production, and integrating aggregates into national freight transport strategies such as "road-to-rail" or "road-to-water" programs.

Our study takes a bottom-up approach by first estimating demand based on socioeconomic drivers and then linking it to supply-side potentials through technological assumptions. While we briefly discussed the implications for freight transport and infrastructure (see Discussion section) as well as included a case study on the spatial distribution of aggregates in the Beijing–Tianjin–Hebei region (Figure S34), detailed logistical modeling is beyond the scope of this material flow–oriented study. We have updated the Discussion section, reading:

In response to the potential shifts in both aggregate demand and CDW generation, economies undergoing industrial transition must coordinate supply–demand dynamics and prepare for corresponding changes in logistics, facility upgrades, and technology deployment. Policy support is essential for optimizing the aggregate industry's value *chain. For instance, life cycle-based tax incentives or subsidies for recycled aggregate products, and the inclusion of aggregates in major freight transition programs—from road to rail or waterway—could support more sustainable practices. Although the aggregate sector is not energy-intensive—with a relatively low carbon footprint of approximately 5 kg CO_2-eq per ton of aggregates72—the rapid changes in supply and utilization patterns necessitate careful planning.*

We agree that logistics and infrastructure planning are crucial to achieving the projected recycling levels, and we see this as an important direction for future interdisciplinary research.

(8) One of the problems with recycled concrete to produce aggregates is the energy consumption needed to crush it, as cement bounds the aggregates very well together: could the author make a link to other environmental dimensions of this aggregate crisis, especially on the energy dimension, and discuss if this shift to much more recycling aggregates could create an excess energy demand in China in a transition already tricky in terms of energy availability?

Response:

Thank you for highlighting this. In the Chinese context, the production processes for recycled aggregates are quite similar to those for manufactured (mechanical) aggregates, mainly involving crushing and screening. In fact, manufactured aggregates often require energy-intensive blasting during extraction, which can result in even higher energy use. Since China's current aggregate supply is already dominated by manufactured aggregates, the energy intensity of shifting to recycled aggregates is expected to be comparable.

More importantly, total energy consumption in the sector—including emissions from associated transport—is driven more by the overall production volume than by differences between production technologies. As our scenarios indicate a significant reduction in future aggregate demand, the sector's total energy use and related emissions are expected to decline accordingly.

As per Chinese policy guidelines, energy use in aggregate production is generally below 10–13 tons of standard coal per 10,000 tons of product (https://www.gov.cn/zhengce/zhengceku/2019-11/13/content_5451478.htm). Similarly, the UEPG reports an average carbon footprint of about 5 kg CO_2-eq per ton of aggregates in Europe (https://www.aggregates-europe.eu/wp-content/uploads/2023/06/UEPG-Roadmap-on-Climate-Change-2023-1_compressed.pdf). These values suggest that the energy intensity of aggregate production is relatively low.

Overall, we do not expect the shift toward recycled aggregates to present significant additional energy demands, especially under a declining demand trajectory.

(9) The uncertainty analysis paragraphs need a deeper interpretation of the results. It is said that "The simulation validated the core model's reliability": a ±49.9% outflow variation across provinces seem quite high, as well as a ±30.9% inflow variation.

Please explain why the authors consider these results validate the model reliability.

Response:

Thank you for this. We agree that the reported variation appears large at first glance. However, it reflects the magnitude of input uncertainties defined in the Monte Carlo simulation. In our analysis, the assumed uncertainty levels for key input parameters ranged from 15% to 60%. Given these settings, the observed provincial-level output variations (±49.9% for outflows and ±30.9% for inflows) are within a reasonable range and thus support the robustness of the model.

Moreover, aggregate-related data are inherently uncertain. For example, previous studies from UNEP report (https://wedocs.unep.org/handle/20.500.11822/28163) have estimated global inflow uncertainties of around 25%, and Krausmann et al (https://www.pnas.org/doi/10.1073/pnas.1613773114) adopted a 60% uncertainty level for aggregate inflows in their Monte Carlo-based assessments. These precedents reinforce the validity of our assumptions and help contextualize the output variability.

Additionally, our model features a relatively high level of spatial and sectoral detail. We conducted separate uncertainty assessments for different end-use categories of aggregates, as shown in Figures S31–S33.

We have revised Supplementary Note 1.5 accordingly to clarify this point.

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). Given that the expected uncertainty ranges assigned to the input parameters in our Monte Carlo simulations were set between 15% and 60%, output deviations within or close to this range indicate that the model is robust. 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 report37, 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.

Former comments:

(10) (1) About risk of climate damage on the robustness of this model's results: based on the literature, I believe that China's coast that is the most built is at high risk. Maybe studies estimated very high physical and financial future damages, for instance "A 2021 study found trillions of dollars of economic activity along China's coastline at risk from climate change, including almost $1 trillion at risk in Shanghai alone"

(https://iopscience.iop.org/article/10.1088/1748-9326/aacc). I don't think this aspect should be neglected as the future is very uncertain, and this aspect should be evocated briefly. In general, scientific modeling tends not to discuss enough limitations of models and uncertainties. Being clear and honest about what a model can say and what it does not account for is the responsibility of researchers.

Response:

Thank you for this good point. We have acknowledged this point in the Discussion section and cited the suggested study.

We added the following statement to the manuscript:

While our analysis focuses on the material flows associated with aggregate production and use, it does not explicitly account for the long-term physical and financial risks that climate-related impacts may pose to coastal infrastructure. This is particularly relevant for China, where highly urbanized and economically vital coastal regions could face substantial damages due to sea level rise and extreme weather events. For example, a 2021 study estimated that nearly $1 trillion of economic activity in Shanghai alone may be at risk74. We acknowledge this as an important limitation of our current modeling framework, particularly in its exclusion of localized risks from extreme climate events. Future research should incorporate spatial exposure and climate vulnerability to more comprehensively assess the long-term sustainability and resilience of the aggregate industry.

(11) b) Thank you for clarifying the sources of some data. It would be good for readers and model's users to specify the language of the source and if it is paid or open-access data in the SI.

Response:

Thank you for your suggestion. All our data sources are open-access. The sources are either in English or Chinese. For non-English sources, we have indicated "in Chinese" in the reference section.

We have added the following statement to the Supplementary Notes:

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.

(12) ii) The issue with lifespan accuracy, which is crucial for this model's output robustness, is that standards/specification lifespans are theoretical, and that real lifespans often exceed standard lifespans. In Eurocode for concrete buildings in Europe, the lifespan is considered to be 50 years, what is clearly not a reality. Can the authors dig into this aspect and find studies comparing standard and real lifespans for construction in China to double-check the accuracy

of these input parameters?

Response:

Thank you. We agree that standard lifespans specified in codes often differ from actual building lifespans, and in many cases, real lifespans exceed design expectations. This is particularly evident in Europe, where numerous buildings have remained in use for over a century despite the 50-year benchmark in codes such as Eurocode.

However, the situation in China is notably different. During recent decades of rapid development, policy-driven demolition and reconstruction have led to many buildings being dismantled well before reaching their theoretical service life. As reported by China Daily, quoting the Vice Minister of Housing and Urban-Rural Development, this has resulted in a generally shorter actual lifespan for buildings in China (https://www.chinadaily.com.cn/china/2010-04/06/content_9687545.htm).

Therefore, we believe the use of lifespan data reflecting these conditions is appropriate. Moreover, the uncertainty ranges used in our model are relatively wide and are intended to accommodate such variability. We have included a note in Supplementary Notes 1.2:

> *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 life14. 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.*

(13) 6) b) I still don't understand the color code, especially: Chinas's east is in purplelike the boxes "final uses on provincial level": what does it mean? The color code and understandability of the figure sould be enhanced.

Response:

Thank you for the suggestion! We have redrawn Figure S4. Apart from the red and blue colors, the other colors in the boxes do not carry any specific meaning in the previous version.

[Figure Redacted]

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.

Response to Reviewer #2:

(1) Additional paragraph based on former comment (7) P8l217:

- thank you for this addition. I believe the strength of the paragraph could be reinforced by being better supported by the literature, in terms of solutions proposed for instance.
- "life cycle-based tax incentives ", "the inclusion of aggregates in major freight transition programs—from road to rail or waterway—could support more sustainable practices.": what do the authors mean exactly?
- Secondly, the aggregate sector may be not energy-intensive, but the global production and transport of aggregates may account for around 1% of current GHGs and could increase if transportation distances increase and transport services do not switch from road to rail or waterway. See https://www.sciencedirect.com/science/article/pii/S0959652623017870
- In the same article, a literature review of virgin aggregate carbon footprint show that "from cradle to customer, the aggregates present a carbon footprint ranging from 3.67 to 38.2 kgCO2eq/t", so the value of 5 kgCO2eq/t you present may not represent the average value.

Response:

We sincerely thank for your thorough and thoughtful comments. We have carefully revised the manuscript in accordance with your detailed suggestions. We also appreciate the references and points you shared, which have helped us further strengthen the quality of the manuscript. We have added these citations and revised the original text accordingly.

The previous figures on the carbon intensity of aggregates were based on a target value (5 kgCO2eq/t) from Chinese policy documents and lacked broader applicability; we have adjusted the phrasing to reflect this.

In addition, we have revised the statements related to aggregate transportation. The updated text now reads:

> *For instance, implementing tax incentives for all stages of recycled aggregate production (e.g., collection, processing, and transportation), along with subsidies for procurement, could enhance economic viability70,71. Recent studies indicate that recycled aggregate concrete can reduce the Global Warming Potential (GWP) by more than 30% compared to concrete made with natural aggregates72; however, the net benefit depends strongly on transport distances, production technology, and mixture design. Given the anticipated large-scale expansion of recycled aggregate use, the total energy consumption and carbon emissions associated with its production and consumption remain substantial. Although the aggregate industry is not considered energy-intensive, with life-cycle carbon footprints ranging from 3.67 to 38.2 kg CO_2-eq per ton, its combined production and transport emissions account for about 1% of global carbon emissions73-75. In China, a carbon intensity target of 5 kg CO_2-eq per ton has been proposed in policy documents as a guiding benchmark for aggregate production57. Among these, transportation contributes a disproportionately large share, exceeding 30%76 and the variability in*

distance and mode introduce further uncertainties in both energy use and emissions. Therefore, optimizing transportation logistics, shortening transport distances, and shifting long-distance haulage from road to rail or waterborne transport can substantially contribute to decarbonization and sustainability in the aggregate sector. In the longer term, deploying electric or low-emission vehicle fleets could further reduce sectoral energy and climate impacts.

(2) Answer to former comment (8): I do not consider this question answered correctly, with correct literature support, in the authors' rebuttal document.

- "manufactured aggregates often require energy intensive blasting during extraction, which can result in even higher energy use": I do not believe this is true, and I would like to see this fact checked based on literature. In https://www.sciencedirect.com/science/article/pii/S0959652623017870, blasting represents 20 to 30% of fossil fuel depletion from regional virgin aggregate production depending on the technology of production (but with a whole part of the production electrified with a very low-carbon intensive electricity). Moreover, in a review comparing recycled versus virgin aggregates (https://www.sciencedirect.com/science/article/pii/S0048969724054603#bb0055) it is said: "Energy savings from recycling are possible but depend on specific conditions, particularly transport distances"
- The same comparative review give clues for a burden-shifting discussion "The size of recycled aggregate and specific mixture design in RAC significantly affect its environmental impact in LCA studies" and on the question of performance adequation "here are contradictory results which need further investigations from tests conducted on the hardened properties of RAC versus NAC, such as freezing and thawing (Frost) resistance, carbonation rate, and chloride penetration", "RAC production phases for cement and aggregate have slightly larger impact than NAC. Environmental impact is significantly influenced by transport distances and modes »
- "Overall, we do not expect the shift toward recycled aggregates to present significant additional energy demands, especially under a declining demand trajectory": I believe it is an important point to discuss in your paper, as circular economy practices are expected by the public to reduce environmental impacts, but it is not always the case

Response:

Thank you for your suggestions and for sharing those important papers.

We acknowledge that our earlier phrasing regarding the energy intensity of blasting in manufactured aggregates was imprecise. Based on the referenced study (https://www.sciencedirect.com/science/article/pii/S0959652623017870) your shared (we thank for this!), blasting accounts for approximately 20-30% of fossil fuel depletion in regional virgin aggregate production, and the overall energy intensity is highly dependent on the degree of electrification and production technology. We have removed or rephrased the previous statement accordingly.

While circular economy measures are often promoted for their environmental benefits, we acknowledge that the net impacts depend strongly on context, particularly transport distances, aggregate quality, and processing technologies. We agree with the review you shared (https://www.sciencedirect.com/science/article/pii/S0048969724054603) that recycled aggregate concrete can sometimes exhibit higher impacts in certain phases (e.g., cement use, pre-treatment) compared to virgin alternatives. These trade-offs, particularly under burden-shifting scenarios, warrant further analysis and clearer communication in future policy design.

We also acknowledge that the environmental and technical performance of recycled aggregate concrete is influenced by mixture design and application-specific requirements. In the reviews your shared (https://www.sciencedirect.com/science/article/pii/S0048969724054603), factors such as freeze-thaw resistance, carbonation rate, and chloride penetration can vary between RAC and NAC. While our current study focuses on material flows and emissions at the sectoral level, further research should examine how these technical parameters affect the feasibility and net benefits of circular aggregate use in specific construction contexts.

Indeed, transport-related emissions represent a dominant share of the aggregate sector's life-cycle carbon footprint, often exceeding 30%. Given the variability in transport distance and mode, this introduces considerable uncertainty into overall emissions and energy use. Therefore, optimizing transport planning, reducing haul distances, and promoting low-carbon transport modes such as rail and inland waterway are essential for emission mitigation in this sector.

Looking ahead, the widespread deployment of electric or alternative fuel vehicles for aggregate transport could further reduce energy consumption and associated emissions. Given that carbon emissions are inherently global and intersectoral, future research should aim to connect changes in aggregate-sector emissions—driven by circular economy measures and projected production volumes—with broader changes in global emissions. This comparison could offer insights for policy and system-level mitigation strategies.

We have made the following revisions in the Discussion section:

> *Recent studies indicate that recycled aggregate concrete can reduce the Global Warming Potential (GWP) by more than 30% compared to concrete made with natural aggregates72; however, the net benefit depends strongly on transport distances, production technology, and mixture design. Given the anticipated large-scale expansion of recycled aggregate use, the total energy consumption and carbon emissions associated with its production and consumption remain substantial. Although the aggregate industry is not considered energy-intensive, with life-cycle carbon footprints ranging from 3.67 to 38.2 kg CO_2-eq per ton, its combined production and transport emissions account for about 1% of global carbon emissions73-75. In China, a carbon intensity target of 5 kg CO_2-eq per ton has been proposed in policy documents as a guiding benchmark for aggregate production57. Among these, transportation contributes a disproportionately large share, exceeding 30%76 and the variability in distance and mode introduce further uncertainties in both energy use and emissions. Therefore, optimizing transportation logistics, shortening transport distances, and shifting long-distance haulage from road to rail or waterborne transport can substantially contribute to decarbonization and sustainability in the aggregate sector. In the longer term, deploying electric or low-emission vehicle fleets could further reduce sectoral energy and climate impacts.*

(3) Answer to former comment (9): "Given that the expected uncertainty ranges assigned to the input parameters in our Monte Carlo simulations were set between 15% and 60%, output deviations within or close to this range indicate that the model is robust": I think that this statement would be more convincing if backed up by adequate literature on statistics/MCS.

Response:

Thank you for this important observation. We agree that the robustness claim should be better grounded in existing literature. In our study, Monte Carlo simulation is used to quantify the uncertainty propagation from input parameters to model outputs. The observed result—that output uncertainty remains within the range of input variability (15–60%)—is not used as a standalone proof of robustness, but as an indicator of proportional sensitivity, consistent with prior studies in dynamic MFA modeling (https://www.pnas.org/doi/full/10.1073/pnas.1613773114; https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12579).

As noted by Nađa Džubur et al. (https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12497), our method aligns with Local Sensitivity Analysis with Uncertain Parameters (LSAu), which is appropriate for MFA models with partially known distributions. For broader methodological grounding, we have added references from the statistical literature on Monte Carlo-based robustness analysis (https://pubs.acs.org/doi/10.1021/es400069b; https://onlinelibrary.wiley.com/doi/10.1111/jiec.12497) to clarify that robustness in this context refers to the stability of model outputs under plausible parameter variation, not to output accuracy per se.

We have revised both the main text and the Supplementary Information accordingly.

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 models37, 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 modeling38 .

(4) Former comment (10): thank you for the addition.

- I would try to make the link between climate change damage, consequential destruction of buildings and infrastructure, and resulting higher demand in aggregates, clearer than it I currently.

- “long-term physical and financial risks that climate related impacts may pose to coastal infrastructure”: “long-term” is quite vague. When could happen damage related to climate change on China’s coasts, in a SSP2 and different RCP futures?
- The 2021 study would be clearer if the time horizon of the damage was given.
- Finally, comparing damage time horizons and the authors’ model time horizon will give insights on how the non-accounted for climate damage could impact the robustness of the model

Response:

Thank you for this thoughtful comment. We find your point regarding climate change damage, the consequential destruction of buildings and infrastructure, and the resulting increase in aggregate demand highly relevant and intellectually stimulating. However, this aspect falls beyond the scope of the present study.

Our model in this manuscript focuses on the baseline demand for aggregates driven by population and economic development, specifically in the housing and infrastructure sectors, with projections extending to 2050. The primary aim is to assess the potential sustainability opportunities associated with circular economy strategies in China’s aggregate sector. Given the study’s focus on circularity and long-term resource management, we are unable to incorporate climate-induced demand shocks in the current model design.

Nonetheless, we agree and excited about that this is an important direction for future research. We are particularly interested in exploring how climate change impacts—such as sea-level rise and increased flood risks—may influence infrastructure vulnerability and future aggregate demand.

We added this into the discussion. The corresponding revisions in the main text are as follows:

While our analysis focuses on the material flows associated with aggregate production and use, it does not explicitly account for the physical and financial risks that climate-related impacts may pose to coastal infrastructure. This is particularly relevant for China, where highly urbanized and economically vital coastal regions could face substantial damages due to sea level rise and extreme weather events. For example, a study estimated that $3.4 trillion of annual sea flood cost would take in China by 2100 under SSP2, 1.5 degree scenario82. This may increase future aggregate demand beyond our current estimates. We acknowledge this as a limitation of the model and highlight the need for future research to integrate climate exposure, spatial risk distribution, and post-disaster reconstruction dynamics.

(5) Former (13): thank you for your modification. I still think the color pattern is confusing: ok to distinguish 2 different types of d-MFA, but then as these categories do not relate to the map areas using the two same colors, it gives false information. If you want to distinguish areas on China’s map, please do not use the same blue and red as for differentiating inflow-driven dy-MFA and stock-driven dy-MFA on Figure S4. Changr adequately the colors on other figures explaining the color code on China’s map, e.g. Figure S2.

(a) : explain any color code you may use on figures with a legend. E.g. Figures S1's and S3's colors, Figure S5, S6, S7, S8
(b) Figures S12, S13, S14: east China is in the same color as "pipeline". Same problem of color codes mixing two types of objects.

Response:

Thank you for your suggestions. We have made the following revisions:

In Figures S1 and S3–S8, some colored blocks previously had no actual meaning and may have caused confusion. We have redrawn these figures to remove non-informative color segments and added a legend to Figure S8 to improve clarity.

In Figures S12–S14, we revised the color scheme used in the pipeline legends to avoid misinterpretation.

General : I have four main concerns, some of them developed in the two following sections.

I) Many studies embrace a similar approach to this study (e.g. 86 studies of road MFA reviewed in this paper, including several prospective studies, and even changes due to climate damage: https://www.sciencedirect.com/science/article/pii/S0921344924001782?via%3Dihub). What is the specific originality of this model/study?

II) Reproducibility of the study is ensured thanks to the open-source code. But transparence of the study is not at the level expected in a Nature Portfolio journal. Especially, references to justify parameters' values (recycling rates, lifespans, material intensities) are not clear

III) Input parameter values such as infrastructure lifespans and material intensity are crucial to the robustness of the output. How certain are these values? The +/-10% uncertainty propagation shows a linearity of the outputs to the inputs, and +/-10% uncertainty of the inputs may be highly underestimated.

IV) How certain the authors are about the substitutability rate of natural aggregates by recycled aggregates (e.g. data in Figure S3)? Downcycling is currently the norm, for many reasons (quality issues, recycling operation complexity, cost, etc.). Little references and justifications are given on the values chosen, while this part of the modeling leads to one of the key messages of the paper. The manuscript needs to strongly support the assumptions taken on that side.

Former comments:

(1) Thank you to the authors for recapping the main lines of their model. What is included in MF3, and how the energy transition, and, more importantly, climate change damage could impact the robustness of the model (e.g., increase need in maintenance/reconstruction of the structures)? The energy sector may require more concrete with the deployment of renewable energy infrastructure, while climate change will have an impact on the lifespan of the structures and the consumption of sand and gravel. If the authors consider SSP2 as the societal narrative, there is little chance to respect the Paris agreement, and we may head to +2.7-+3.1°C by the end of the century compared to re-industrial temperatures, what would have strong impacts in terms of infrastructure damage and aggregate consumption even by 2050.

(2) (3) Thank you for the author's clarifications. The title only mentions sand, while sand and gravel – i.e., aggregates according to the author's definitions - are covered by the model. I still believe the title should be modified, because "sand" does not reflect the studied object, and sand has a specific history of scientific publication with specific stakes that are not the main point of this publication. Moreover, I believe sand is a much smaller share of total aggregates in volume/weight than other types of aggregates. So using sand gives a distorted view of the content of the article.

(3) I have serious doubts on the reliability of the average lifetimes considered, and I question the values of the material intensity chosen too.

   a. First, are the sources in column 6 of table S11 for lifespans, numbers of unit of each category of stock, and material intensities, or only lifespans? We need to follow the sources for each category of value, otherwise the study is not transparent.

   b. Secondly, when I check some of the references given, it is hard, sometimes impossible, to find the data and assess its robustness. For instance: Reference [51] “National Bureau of Statistics of China. *National Data*, 266 <http://www.stats.gov.cn/english/ (accessed Nov 26, 2023)> (1949-2022)” is a source for the values of buildings, roads, railways... but the link brings to a general request webpage, and typing “building lifespan” does not provide any document/data. Please be more specific in the author’s references to be fully transparent. Same for all the references to Chinese yearbooks/statistics (e.g., [60]-[63]): where exactly can we find the values? Is there a name of chapter/specific dataset the authors use? Reference [52] : the material flows evaluated are for construction and demolition only, not maintenance. It means that if material intensity are derived from this study, it is underestimated compared to a full life cycle approach where inflows must consider construction/maintenance/reconstruction to be complete. Reference [53]: an average lifespan of 30 and 20 years is indeed considered in this study for urban and rural residential buildings, but [53] is not the source of these values: it quotes Song 2004 and the Center for Housing Industrialization 2011. None of the study is accessible to me so I cannot check the quality of these estimates. + Please always cite the original study/ies, not derived studies using the values from the original studies.

      i. Type of data and quality: to perform uncertainty propragation, the Pedigree Matrix approach gives a classification of the quality of the data depending on how it was produced. For instance, in terms of completeness, using statistical data for the China is the best approach for lifespans and material intensities, rather than using single values/expert estimates. If some data are theoretical (such as lifespans from construction codes/standard for instance), they are highly uncertain, conclusions are not robust, and recommendations should not be emitted. Could the authors qualify the quality of their main parameters' values (e.g. lifespans and material intensities) using for instance the Pedigree Matrix approach?

ii. Especially, I find lifespans quite short for: building in general (and especially residential buildings, plus there is an inconsistency: in Table S11 for residential buildings, values between 25-35 years are considered while authors have stated elsewhere in the text "The service lifespan of residential buildings in China has traditionally been much shorter than that in developed economies, typically ranging from 30 to 40 years.") and roads (many construction standard outside of China consider lifespans of 20 and 30 years, resp. for secondary and main roads. And the real lifespans exceed most of the time the theoretical lifespan). Moreover, for roads, different layers of the infrastructure have different lifespans, superficial layers having globally much shorter lifespans than deeper layers. Does the model consider a weighed lifespan average over the different layers, depending on the category of roads and their thickness per layer? It would change a lot the quantity of aggregates consumed overtime to have this type of realistic approach. For ballast-based railroads, it also has different layers of materials (ballast, blankets and subgrades) with different lifetimes. Maintenance of the ballast includes over the lifetime of the infrastructure refilling, partial changes, and finally a complete change, each of these activities generating input and output flows. The author's can find an example of a maintenance plan in the section 2.4.6 of this article : https://link.springer.com/article/10.1007/s11367-019-01727-2. For a concrete bed railway, the lifetime will also be different. What kind of railways are built in China and how these different lifespans have been considered in the model?

Please explain how the authors consider these different lifespans for the different parts of the road and rail infrastructure, as a fine modeling is crucial to the estimated input and output aggregate flows in the model. The authors need to explicit better what are the data considered for the material intensity of the infrastructure. Are they values on the entire life cycle, or just for the construction, without the maintenance? I know the authors provide their code, but it is not self explanatory, and the model must be explicated finely enough in the SI.

(5) (6) About the uncertainty analysis conducted: the authors conduct a Monte Carlo analysis with a +/- 10 % normal distribution range with 1000 runs. First, how a +/- 10 % normal distribution range can be proven as realistic/representative of the natural variability of the input values? It seems absolutely too low to me. Secondly, 1000 runs is a default value but is low (see http://link.springer.com/10.1007/s11367-019-01698-4). How these choices affect the result of the Monte Carlo simulation? Last, the analysis shows a linearity of the output uncertainty to the input uncertainty. The question of quality of input data addressed above is thus crucial to be addressed.

+ I think this part of the manuscript needs to be rephrased: “"a Monte Carlo simulation method across 1000 iterations, allowing parameter fluctuations within a ±10% normal distribution range, achieving 99.5% confidence.". It is unclear, and normal distributions have two parameters: the mean and the variance. +/-10% would be rather given for a uniform distribution.

(7) the additions to the conclusions are to my point of view still very general, similar to what has already been published in the past, and not specific enough to the model done. The transition from the object of the model – aggregates – to the specific sand crisis is, to my point of view, clumsy.

Additional points

a) The information conveyed in table S11 would me more interesting for entire China than for Beijing to give an overview of the infrastructure stock, and lifespans / material intensity intervals in the country.
b) Figure S4 : I don’t understand the color code. Why 10 boxes are represented for the final uses, but the text says “8 category, 30 sub-category”: it does not match (+ typos) + the “lifetime distribution” curve and box make think that probability distributions are considered for lifespan values, while according to the table the authors shared in their rebuttals, average lifespans seem to be considered by type of infrastructure and region.
c) Why are there 8 categories / 10 categories of final uses according to figure S4, 17 final uses in the projection on demand side in Figure S5, and 9 final uses in Figure S8? This illustrates why the methodology is hard to follow.
d) Recycling rates, as well as all parameter’s values, need to be supported more strongly. Little references are given. For instance, all the figures from Tables S3 and S4 need to be understandable for the readers. Where do they come from? E.g. “According to the "China Resource Comprehensive Utilization Annual Report" and expert consultations, the utilization rates of aggregate waste”: no reference to the report, what kinds of experts?. Another example “Under the baseline scenario, the recycling and downcycling rates for aggregate waste from various end uses are benchmarked against the prevailing conditions in 2020, as follows:”: no reference is given.
e) No consideration on reducing the development of infrastructure has been done, while reducing end-use consumption is a key aspect of the transition
f) Recycling may bring other environmental problems: energy consumption and others. Tailings request a lot of energy to be transformed in usable aggregates,

leachate can contaminate the infrastructure environment in metals and increase toxicity. It would be wise to address in the conclusion potential burden-shiftings from some of the strategies proposed to the resource stake.

(8) “Sand and gravel issues are often overlooked – in part because they are so abundant – “: overlooked by who? Not researchers at least considering the number of articles, and there are even articles for the public, and documentaries about the sand crisis.

(9) It is a general comment. The reader should not have to struggle to understand the sources of the values taken, and all the parameter’s values need to be sourced in the method part.

(18) “for most modern construction”: contemporary would be better than modern maybe

(21) “Supply-side changes are important and less environmentally impactful resources
include crushed rocks from quarries (crushed stones or manufactured aggregates; see the definition in the Methods section), secondary aggregates from construction and demolition waste (CDW) and ore-sand (a by-product of mineral processing).”: this sustainability ranking is still dependent on the environmental indicators the author’s consider. I suggest the authors nuance “less environmentally impactful resources”.

(35) what are “the socioeconomic impacts of the COVID-19 pandemic”

(41) I would remove all the references to the “sand crisis” as the scope of the paper is broader as it deals with all the aggregates

We thank the authors for the modifications done on the article. It has been significantly improved. Nevertheless, I believe it still needs to be enhanced to align with Nature portfolio's standard.

Part I - The text has improved, but to my opinion it is not finalized yet. The "main" particularly does still have structure flows, redundancy, and English clumsiness/vagueness.

For instance, there is a lot a redundancy along the text about the specification of some terms, and the text has to be cleaned to become fit and lean. I will just give a few examples but many can be found in the text:

For instance, p1l47: "sand, gravel, and stone. These substances, known as aggregates". Then, a second entire paragraph talks about aggregates (the term is used 4 times from p1l54-l60). Then paragraph 3, p1l62: "Aggregates (sand, gravel, and crushed stone) ».

Usage of brackets : it cuts the text, interrupt the reading flow, and can bring confusion, especially when not located at the end of a sentence. Example p1l76: "Some argue this trend has escalated into a sand (and gravel) crisis", p1l87 "holistic approach for addressing the sand (and gravel) crisis »: what does (and gravel" indicate? A lower level of alarm? Then write it clearly. As it is, it evocates the ideas of the authors are unclear.

P4l126 "(based on Shared Socioeconomic Pathway 240, SSP2)": the authors can just put SSP2 in brackets, and justify its used, like: based on Shared Socioeconomic Pathway 2 (SSP2) representing a middle of the road pathways40.

The use of the term "sustainability" in different places is very vague. What do the author refer to? Social, economic, or environmental sustainability? Triple bottom line sustainability?

The manuscript includes a lot of "be verbs" that need to be avoided as much as possible in a scientific article. Some example, but please review your manuscript thoroughly:

- P1L51: "That's » (+ improper in an article)
- "there is", "is" "are", "this is"

Vital is repeated 9 times in the text.

Part II - In terms of scientific content and modeling:

In the end, the authors investigated a baseline scenario and then only scenarios focusing on solving the aggregate crisis. No pessimistic scenario was considered in terms of aggregate consumption, such as scenarios with higher growth rates and consumption increase. It is important to specify that in the text and potentially in the title

P8l217: “Recycling of aggregate waste in China is expected to rise from 733.7 Mt in 2021 to 4.5 Gt”: it would be interesting to understand a bit the concrete logistic changes needed for that (Need for new infrastructure? Any operational stake for decision-makers?)

One of the problems with recycled concrete to produce aggregates is the energy consumption needed to crush it, as cement bounds the aggregates very well together: could the author make a link to other environmental dimensions of this aggregate crisis, especially on the energy dimension, and discuss if this shift to much more recycling aggregates could create an excess energy demand in China in a transition already tricky in terms of energy availability?

The uncertainty analysis paragraphs need a deeper interpretation of the results. It is said that “The simulation validated the core model's reliability”: a ±49.9% outflow variation across provinces seem quite high, as well as a ±30.9% inflow variation. Please explain why the authors consider these results validate the model reliability.

Former comments:

(1) About risk of climate damage on the robustness of this model’s results: based on the literature, I believe that China’s coast that is the most built is at high risk. Maybe studies estimated very high physical and financial future damages, for instance “A 2021 study found trillions of dollars of economic activity along China’s coastline at risk from climate change, including almost $1 trillion at risk in Shanghai alone” (https://iopscience.iop.org/article/10.1088/1748-9326/aacc). I don’t think this aspect should be neglected as the future is very uncertain, and this aspect should be evocated briefly. In general, scientific modeling tends not to discuss enough limitations of models and uncertainties. Being clear and honest about what a model can say and what it does not account for is the responsibility of researchers.

b) Thank you for clarifying the sources of some data. It would be good for readers and model’s users to specify the language of the source and if it is paid or open-access data in the SI.

ii) The issue with lifespan accuracy, which is crucial for this model’s output robustness, is that standards/specification lifespans are theoretical, and that real lifespans often exceed standard lifespans. In Eurocode for concrete buildings in Europe, the lifespan is considered to be 50 years, what is clearly not a reality. Can the authors dig into this aspect and find studies comparing standard and real lifespans for construction in China to double-check the accuracy of these input parameters?

6) b) I still don’t understand the color code, especially: Chinas’s east is in purplelike the boxes “final uses on provincial level”: what does it mean? The color code and understandability of the figure sould be enhanced.

Additional paragraph based on former comment (7) P8l217:

- thank you for this addition. I believe the strength of the paragraph could be reinforced by being better supported by the literature, in terms of solutions proposed for instance.
- “life cycle-based tax incentives “, “the inclusion of aggregates in major freight transition programs—from road to rail or waterway—could support more sustainable practices.”: what do the authors mean exactly?
- Secondly, the aggregate sector may be not energy-intensive, but the global production and transport of aggregates may account for around 1% of current GHGs and could increase if transportation distances increase and transport services do not switch from road to rail or waterway. See https://www.sciencedirect.com/science/article/pii/S0959652623017870
- In the same article, a literature review of virgin aggregate carbon footprint show that “from cradle to customer, the aggregates present a carbon footprint ranging from 3.67 to 38.2 kgCO2eq/t”, so the value of 5 kgCO2eq/t you present may not represent the average value.

Answer to former comment (8) : I do not consider this question answered correctly, with correct literature support, in the authors’ rebuttal document.

- “manufactured aggregates often require energy intensive blasting during extraction, which can result in even higher energy use”: I do not believe this is true, and I would like to see this fact checked based on literature. In https://www.sciencedirect.com/science/article/pii/S0959652623017870, blasting represents 20 to 30% of fossil fuel depletion from regional virgin aggregate production depending on the technology of production (but with a whole part of the production electrified with a very low-carbon intensive electricity). Moreover, in a review comparing recycled versus virgin aggregates (https://www.sciencedirect.com/science/article/pii/S0048969724054603#bb0055) it is said: “Energy savings from recycling are possible but depend on specific conditions, particularly transport distances”
- The same comparative review give clues for a burden-shifting discussion “The size of recycled aggregate and specific mixture design in RAC significantly affect its environmental impact in LCA studies” and on the question of performance adequation “here are contradictory results which need further investigations from tests conducted on the hardened properties of RAC versus NAC, such as freezing and thawing (Frost) resistance, carbonation rate, and chloride penetration”, “RAC production phases for cement and aggregate have slightly larger impact than NAC. Environmental impact is significantly influenced by transport distances and modes »
- “Overall, we do not expect the shift toward recycled aggregates to present significant additional energy demands, especially under a declining demand trajectory”: I believe it is an important point to discuss in your paper, as circular

economy practices are expected by the public to reduce environmental impacts, but it is not always the case

Answer to former comment (9): "*Given that the expected uncertainty ranges assigned to the input parameters in our Monte Carlo simulations were set between 15% and 60%, output deviations within or close to this range indicate that the model is robust":* I think that this statement would be more convincing if backed up by adequate literature on statistics/MCS.

Former comment (10): thank you for the addition.

- I would try to make the link between climate change damage, consequential destruction of buildings and infrastructure, and resulting higher demand in aggregates, clearer than it I currently.
- "long-term physical and financial risks that climate related impacts may pose to coastal infrastructure": "long-term" is quite vague. When could happen damage related to climate change on China's coasts, in a SSP2 and different RCP futures?
- The 2021 study would be clearer if the time horizon of the damage was given.
- Finally, comparing damage time horizons and the authors' model time horizon will give insights on how the non-accounted for climate damage could impact the robustness of the model

Former (13): thank you for your modification. I still think the color pattern is confusing: ok to distinguish 2 different types of d-MFA, but then as these categories do not relate to the map areas using the two same colors, it gives false information. If you want to distinguish areas on China's map, please do not use the same blue and red as for differentiating inflow-driven dy-MFA and stock-driven dy-MFA on Figure S4. Changr adequately the colors on other figures explaining the color code on China's map, e.g. Figure S2.

(a) : explain any color code you may us eon figures with a legend. E.g. Figures S1's and S3's colors, Figure S5, S6, S7, S8
(b) Figures S12, S13, S14: east China is in the same color as "pipeline". Same problem of color codes mixing two types of objects.