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# Toward a low-carbon and circular building sector: Building strategies and urbanization pathways for the Netherlands

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## Abstract

Buildings are an important part of society's environmental impacts, both in the construction and in the use phase. As the energy performance of buildings improve, construction materials become more important as a cause of environmental impact. Less attention has been given to those materials. We explore, as an alternative for conventional buildings, the use of biobased materials and circular building practices. In addition to building design, we analyze the effect of urbanization. We assess the potential to close material cycles together with the material related impact, between 2018 and 2050 in the Netherlands. Our results show a limited potential to close material cycles until 2050, as a result of slow stock turnover and growth of the building stock. At present, end-of-life recycling rates are low, further limiting circularity. Primary material demand can be lowered when shifting toward biobased or circular construction. This shift also reduces material related carbon emissions. Large-scale implementation of biobased construction, however, drastically increases land area required for wood production. Material demand differs strongly spatially and depends on the degree of urbanization. Urbanization results in higher building replacement rates, but constructed dwellings are generally small compared to scenarios with more rural developments. The approach presented in this work can be used to analyze strategies aimed at closing material cycles in the building sector and lowering buildings' embodied environmental impact, at different spatial scales.

KEYWORDS
building material, circular economy, climate change, geographic information systems, industrial ecology, material flow analysis

## 1 | INTRODUCTION

Buildings are a significant part of society's environmental impact, both in the use phase via heating, cooling, and electricity use, and in the construction of the building via the extraction, production, and use of building materials (IEA, 2020; Ramesh et al., 2010). Significant progress has been made in improving the energy performance in the use phase, for example, via renewable energy supply, low-carbon heating technologies, and improved insulation (D'Agostino et al., 2021; Sartori & Hestnes, 2007). These developments have resulted in an increasing share of low-energy and zero-energy buildings: highly energy efficient buildings with a renewable energy supply. Efforts are now increasing to reduce emissions related to production of construction materials, as these can be significant, especially when use-phase emissions are minimized (Blengini & Di Carlo, 2010; Heeren et al., 2015; OECD, 2019; Pauliuk & Heeren, 2021).

The manufacturing of construction materials was already responsible for 11% of global greenhouse gas (GHG) emissions in 2018, largely stemming from cement and steel production (IEA, 2018). The choice of construction materials is therefore an important consideration for reducing environmental impacts related to buildings. In the literature we find two main strategies to do that: biobased material use and circular building design.

A shift from conventional construction materials to biobased alternatives has substantial climate benefits (Andersen et al., 2021; Buchanan & Honey, 1994; Dodoo et al., 2012; Heeren et al., 2015; Hertwich et al., 2019). An increased implementation of wooden construction and its effect on cumulated embodied GHG emissions have been studied on a national (Heeren & Hellweg, 2019) and a global scale (Zhong et al., 2021). Wood cultivation is also land intensive, and without sustainable management of forest resources, carbon is simply inefficiently displaced from forests to urban regions (Pomponi et al., 2020). Consideration of land-use implications is therefore important when considering large-scale implementation of wood and other biobased construction materials.

Previous literature on circular building strategies has primarily focused on assessment of the recovery potential of demolished building materials (Mhatre et al., 2021). Significant amounts of greenhouse gas emissions can be saved by recycling construction materials (Ginga et al., 2020; Zhong et al., 2021). Implementing circular strategies in the building design, such as design for disassembly and deconstruction (Eberhardt et al., 2019; Rios et al., 2015), and alternative material use (Orsini & Marrone, 2019) can further increase the recovery potential. While these strategies show potential to reduce buildings' embodied carbon emissions, their implementation so far remains limited (Kanters, 2020; Rios et al., 2015) and only few studies assessed the environmental benefits of circular building strategies (Gallego-Schmid et al., 2020; Hossain & Ng, 2018).

Not only the building strategy, but also the level of urbanization affects material stock and flow dynamics. Urbanization typically leads to the construction of smaller dwellings than rural building development (i.e., apartments instead of single-family houses) but may also lead to higher building replacement rates as a result of building densification (PBL, 2021). Geospatial data present a valuable source to assess building densities and assess building construction and demolition rates for different levels of urbanization. So far, geospatial data have been used to study material stocks on an individual building level (Kleemann et al., 2017; Mastrucci et al., 2017; Verhagen et al., 2021), assess the evolution of material stocks in the past (Guo et al., 2021; Miatto et al., 2019; Tanikawa & Hashimoto, 2009; Tanikawa et al., 2015), and for prospective dynamic stock modeling by combining stock scenarios with estimated building lifespans (Heeren & Hellweg, 2019; Yang et al., 2022). The effect of spatial configuration of the building stock, that is, degree of urbanization, on the dynamics of material stocks and flows has, as far as we are aware, not been studied yet.

In this paper we compare biobased and circular building strategies to conventional (concrete-based) buildings. For these three building strategies we address the following research question: how do these building strategies affect the material stocks and flows of the Dutch building sector toward 2050, what is the potential to close material cycles, and what is the environmental impact related to the production of these materials? The Netherlands presents an interesting case study, as it has set the ambitious policy goal to make a transition toward a circular economy by 2050, and lower greenhouse gas emissions by 95% in 2050 compared to 1990. All three strategies conform to the nearly zero-energy building standard set out for the Netherlands (RVO, 2017). For each of the building strategy scenarios, we investigate the effect of urbanization on the basis of spatially modeled building construction and demolition activities. The circularity potential is assessed by comparing the material demand with the recycled material outflow. In the final analysis step, we link the primary and secondary material share to their associated embodied environmental impacts.

## 2 | METHODS

### 2.1 | Model overview

In this study, we combined spatial modeling with material flow analysis (MFA) to assess material stock dynamics in the Dutch building sector. MFA is a widely used method to quantify material stocks and flows, their dynamics over time, and their circularity (Fishman et al., 2021; Krausmann et al., 2017; Wiedenhofer et al., 2019). Building stock dynamics were modeled between 2018 and 2050 for three spatially explicit urbanization pathways: Urban, Connected, and Rural. These were included in three building strategy scenarios (Conventional, Biobased and Circular, see Section 2.2.2.), specific for 14 construction materials (Section 2.2.3). Material stocks and flows for building construction and demolition were modeled. Building renovation activities were not included in the analysis. We assessed end-of-life recycling rates (RR) and the maximum recycled content (MRC) of the inflow, and link material demand with LCA data to calculate GHG emissions and land use related to material production. The material flows can be aggregated to match policy at different scale levels. Figure 1 presents an overview of the model approach. In the next sections, we explain the model and scenarios in further detail (refer to Supporting Information S1-1 for modeling details).

We distinguished three types of dwellings: detached houses, row houses, and apartments, and four non-residential building types: industry, offices, retail, and services. We used a bottom-up approach, as described by Tanikawa et al. (2015) to calculate the building stock in 2018, based

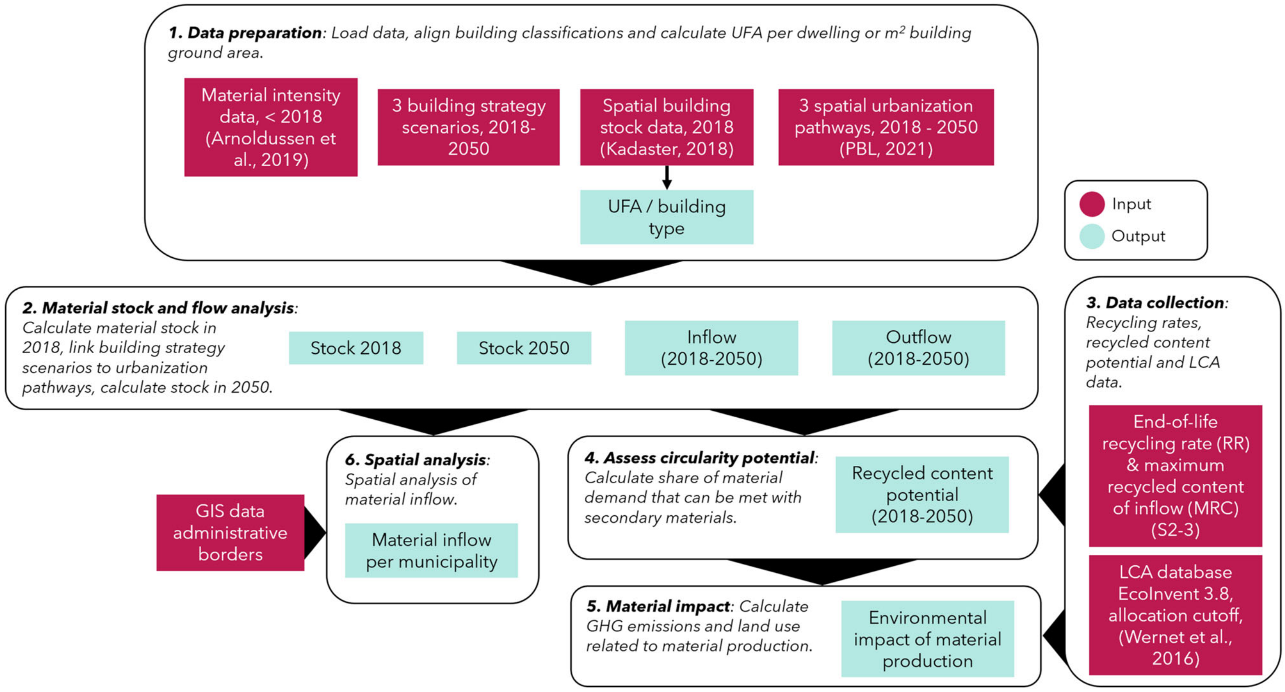


**FIGURE 1** Model overview

on the BAG dataset (BAG, 2018). This GIS-based dataset contains all buildings in the Netherlands with information on location, building type, useful floor area (UFA), and construction year. UFA refers to the surface area, measured at floor level, between the partitioning structures that enclose a space or group of spaces. We linked this dataset to material intensities specified for Dutch buildings for four building period cohorts (<1945, 1945–1970, 1970–2000, and 2000–2018), derived from Arnoldussen et al. (2019).

The building stock in 2018 was used as a starting point for spatially explicit pathways for cumulative building construction and demolition between 2018 and 2050, modeled on a 100 by 100 m resolution. The intensity and location of building activities were modeled for three urbanization pathways (Urban, Connected, and Rural) and were based upon land-use indicators (land-use type, building characteristics, and building density) and socio-economic indicators (population and economic growth) (PBL, 2021). Dwellings were modeled in numbers, and non-residential buildings were modeled in $m^2$ ground area. We refer to Supporting Information S1-2 for details on the spatial model. To determine the UFA per dwelling or $m^2$ ground area in the urbanization pathway data, we calculated the mean values per building type for the building stock in 2018 (BAG, 2018). We assumed a constant floor area per dwelling or ground area between 2018 and 2050. Changes in UFA were considered in a sensitivity analysis. The urbanization pathways in terms of UFA were then linked to building material intensities in kg of specific materials per $m^2$ UFA for three building strategy scenarios (Conventional, Biobased, and Circular).

We calculated what share of the demolition waste (*D*), per material (*m*) can be recycled for new construction. Only high-end recycling was considered, referring to the production of secondary material that can be used for a similar application as its primary application. Reuse at component level was not considered, as we assumed that materials that become available from the urban mine between 2018 and 2050 originate from buildings that do not follow circular design principles. End-of-life recycling rate (RR) refers to the share of the demolition flow that is recycled and maximum recycled content (MRC) refers to the maximum share of secondary material in the inflow. RR and MRC were based on literature and current practices in the Dutch or European recycling industry (refer to Supporting Information S2-3 for details). If the recycled quantity of the demolition flow is larger than the maximum share of secondary materials in the inflow, a part of the demolition flow cannot be reused within the building sector. When the recycled demolition materials are smaller in size than the maximum share of secondary material in the inflow, all secondary materials can be repurposed (Equations 1 and 2):

$$\textit{if}\ \mathrm{RR_m} * D_\mathrm{m} \geq I_\mathrm{m} * \mathrm{MRC_m} : R_\mathrm{m} = I_\mathrm{m} * \mathrm{MRC_m} \quad (1)$$

$$\textit{elif}\ \mathrm{RR_m} * D_\mathrm{m} < \mathrm{MRC_m} : R_\mathrm{m} = D_\mathrm{m} * \mathrm{RR_m} \quad (2)$$

$I_m$ and $R_\mathrm{m}$ present the material inflow and the recycled secondary material flow, respectively.

In a sensitivity analysis, we assessed how the share of secondary material changes when we apply actual RR instead of best practice RR. Actual RR was based on current practices in the Netherlands and Europe, while best practice RR presents the current maximum. To explore the limits in the recycled content, we also assessed how the results change when applying a 100% RR.

We assessed GHG emissions related to material production on the basis of the life cycle inventory (LCI) database EcoInvent version 3.6 (Wernet et al., 2016) and supplemented the dataset where needed with values from scientific literature (see the Supporting Information S2-2 for an overview). For primary material production, we assessed the impact from cradle to material production. For secondary material production, we assessed the GHG emissions for building demolition, material transportation, recycling, and secondary material production.

The area of land related to material production was calculated. Because land occupation ($m^2$ year) was found to be significantly higher for wood than for other materials (see Supporting Information S2-5 for details), we calculated the total area of land ($m^2$) required for wood production. EcoInvent background documentation was used to obtain the yield and production time in $m^3/m^2$ for softwood and hardwood production. Losses in the supply chain (e.g., logging, sawing, drying, and planning) were accounted for, and were based on the production processes in EcoInvent version 3.6 (Wernet et al., 2016).

The obtained results have a spatial dimension. We spatially assessed the building construction activities for pathways Urban and Rural. Although the results are generated for the entire country, here we focused on one municipality to assess the effects of urbanization at a high spatial resolution (100 × 100 m). The municipality of Amsterdam was taken as an example. The aggregated results per municipality, on a national scale, can be found in Supporting Information S1-2.

## 2.2 | Scenarios and parameters

### 2.2.1 | Socio-economic developments

Socio-economic developments were based upon the Dutch scenarios for welfare and human development (van Eck et al., 2020). The scenarios are quantified for indicators such as demographic and economic development, regional development and urbanization, mobility, agriculture, and energy consumption. Population growth, household size, and sector specific job developments presented important indicators for this study. Demand for workspace in different sectors was based upon estimated developments of the economic sector and developments in the surface area per job (PBL, 2021). The number of jobs in the industry sector is expected to decrease after 2030, while various service sectors will continue to grow, for example, in health care.

A distinction was made between scenarios High and Low. In this study, we focused on scenario High, which combines high economic growth (2% per year) with a relatively strong population growth (19% growth between 2018 and 2050). We assessed how the results change for scenario Low in a sensitivity analysis. In scenario Low, economic growth is moderate (1% per year) and is accompanied by low population growth (3% growth between 2018 and 2050).

### 2.2.2 | Urbanization pathways

Three spatial urbanization pathways were modeled: Urban, Connected, and Rural (PBL, 2021). These were chosen to differentiate between density of buildings and the distribution between different types of buildings (e.g., more detached houses in pathway Rural).

- Pathway Urban: construction of new buildings is concentrated in urbanized areas. Building densification results in high demolition rates, for example, the replacement of a detached house with apartments. In this pathway, the construction of apartments is high compared to row houses and detached houses. Locations in close proximity to amenities have priority for building construction.
- Pathway Connected: construction of new buildings concentrates in proximity of public transportation nodes (train, metro, bus, or tram stations). Similar to Urban, the density of buildings is high and the construction of dwellings is dominated by apartments.
- Pathway Rural: urbanization of the countryside is emphasized. Construction takes place on agricultural land and in unprotected nature. The density of building construction is relatively low compared to the other urbanization pathways. The construction of dwellings is dominated by detached houses and row houses. Locations with good car accessibility are prioritized for building construction. Table 1 presents an overview of the most important scenario assumptions.

In all scenarios, protected buildings (e.g., historic buildings) and buildings constructed after 1985 do not qualify for demolition. Furthermore, buildings cannot be constructed in protected nature areas or drinking water production areas. See Supporting Information S1-2 for further details on the urbanization pathways.

**TABLE 1** Overview of model assumptions for the urbanization pathways. We refer to the Supporting Information (S1-2) for spatial modeling details

| | | Pathway | | |
|---|---|---|---|---|
| **Variable** | **Unit** | **Urban** | **Connected** | **Rural** |
| Newly constructed dwellings | units | 2.47E+06 | 2.22E+06 | 2.00E+06 |
| of which apartments | % | 59% | 47% | 23% |
| of which row houses | % | 37% | 46% | 60% |
| of which detached houses | % | 4% | 7% | 17% |
| % of legacy dwelling stock (2018) demolished | % | 6% | 3% | 0% |
| Newly constructed non-residential area | $m^2$ ground area | 2.66E+07 | 2.70E+07 | 2.39E+07 |
| % of legacy non-residential building stock (2018) demolished | % | 1% | 1% | 0% |

### 2.2.3 | Building strategy scenarios

The material intensities of buildings constructed until 2018 were specified for 7 building types, 14 construction materials (steel and iron, copper, aluminum, other metals, wood, concrete, clay brick, other construction materials, glass, ceramics, plastics, insulation [further divided into 6 insulation materials], and others), and 4 building period cohorts (<1945, 1945–1970, 1970–2000, >2000), and were based upon inspections of Dutch buildings and technical reports (Arnoldussen et al., 2019). Three scenarios were created for the material composition of newly constructed buildings in the period of 2018 to 2050, based upon recent developments in the construction sector: Conventional, Biobased, and Circular. Material intensities differ per building type for each scenario (we refer to S1-3 and S2-1 in the Supporting Information for material intensity details). In all scenarios, material intensities change as a result of conformation to the "Nearly Zero-Energy Building" (NZEB) norm, which requires an enhanced environmental performance of buildings (RVO, 2017). Implementation of this norm results in an increased application of insulation materials, double glazing, and a shift in the heating system from central heating toward heat pumps.

- Scenario Conventional: 80% of the constructed buildings are concrete based. Twenty percent of the constructed buildings are biobased, as a result of increased scientific and political interest in biobased construction (Heeren et al., 2015; Hertwich et al., 2019; Şengül et al., 2020).
- Scenario Biobased: wooden construction becomes the norm for new buildings. Concrete supporting structures are replaced with timber frames and concrete floors and walls are replaced with cross-laminated wooden elements. Cross-laminated timber is used in offices and apartments, and wooden frame construction with cross-laminated timber floors is applied in ground-level dwellings, schools, and healthcare buildings. Sand cement floors are replaced with gypsum fiber boards, PUR/PIR insulation is replaced with wood fiber insulation, brick cladding is replaced with wooden facades, and aluminum window and door frames are replaced with wooden equivalents. We refer to S1-3 in the Supporting Information for more details. We assume that 80% of the constructed buildings are biobased (Şengül et al., 2020).
- Scenario Circular: circular design strategies are implemented in buildings, including detachable connections and reusable components. This results in changes in the material composition of the buildings. Concrete supporting structures are replaced with steel frames in apartments and offices, PUR foam isolation is replaced with rockwool, traditional bricks are replaced with detachable bricks, and gypsum block and sand-lime brick inner walls are replaced with detachable aluminum frames. We assume that 20% of constructed buildings are biobased.

## 3 | RESULTS

### 3.1 | Building UFA stock and flow dynamics

The construction rates in square meter UFA for the three urbanization pathways range between 309 and 330 million $m^2$ (Figure 2). The majority of constructed area consists of residential floor area. Differences between the pathways are significantly larger for building demolition. In pathway Rural less than 1 million square meters are demolished, while 68 million square meters are demolished in pathway Urban. The higher demolition rates in pathway Urban stem from high building densification rates, resulting in more building replacements. While the number of constructed dwellings is higher in pathways with more urbanization, they are typically smaller (largely apartment instead of row houses and detaches houses), leading to only a moderately higher construction rate than pathways Connected and Rural. Similar to dwellings, the construction and demolition rates of non-residential buildings is higher in Urban and Connected than in Rural. The majority of the non-residential constructed buildings have an office or service function.

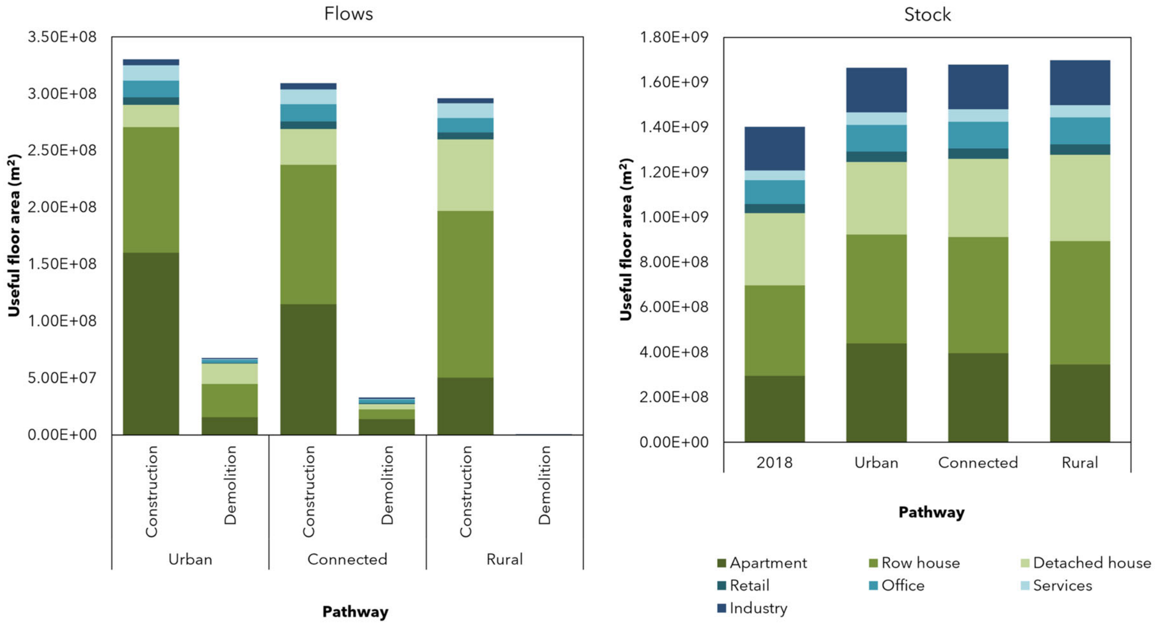


**FIGURE 2** Cumulative inflow and outflow in m$^2$ useful floor area (UFA) between 2018 and 2050 and stock in m$^2$ UFA for 2018 and 2050 for the three urbanization pathways. Underlying data for this figure can be found in Supporting Information S3.

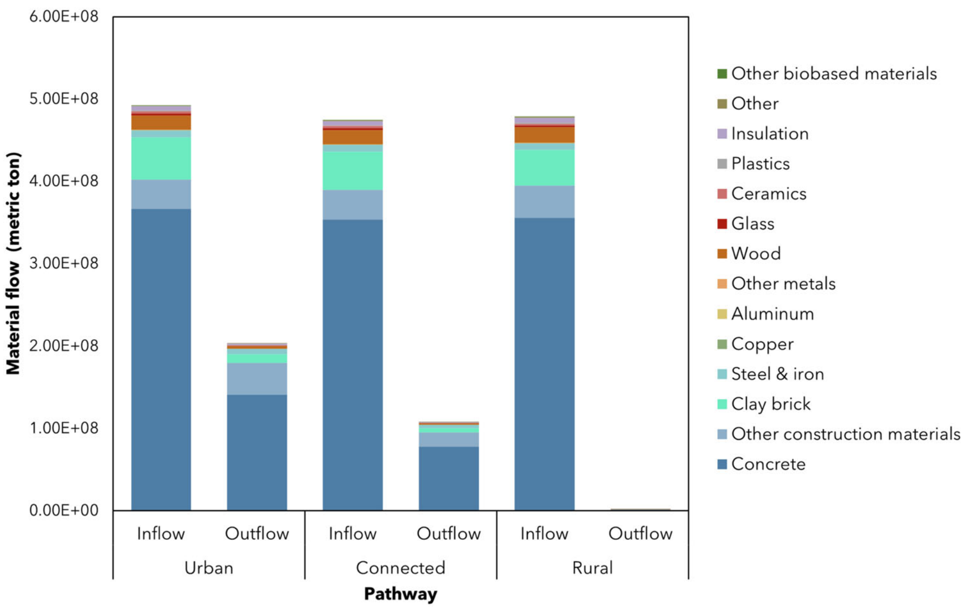


**FIGURE 3** Cumulative material inflow and outflow between 2018 and 2050 for the three urbanization pathways (Conventional building strategy). Underlying data for this figure can be found in Supporting Information S3.

The building stock in UFA increases with 19% (Urban) to 21% (Rural) compared to 2018 (Figure 2). Differences in stock growth between the pathways are minor compared to differences in flows, as the stock in 2018 is already substantial in size. Stock growth is slightly higher in pathway Rural, because the constructed dwellings are typically larger than pathways Urban and Connected and few buildings are demolished.

## 3.2 | Material stock and flow dynamics

For the Conventional building strategy, total material demand varies between 474 and 492 (metric) million ton (Figure 3). Urbanization trends only marginally affect material demand, with slightly higher values for pathway Urban compared to pathway Connected and Rural. Material demand is

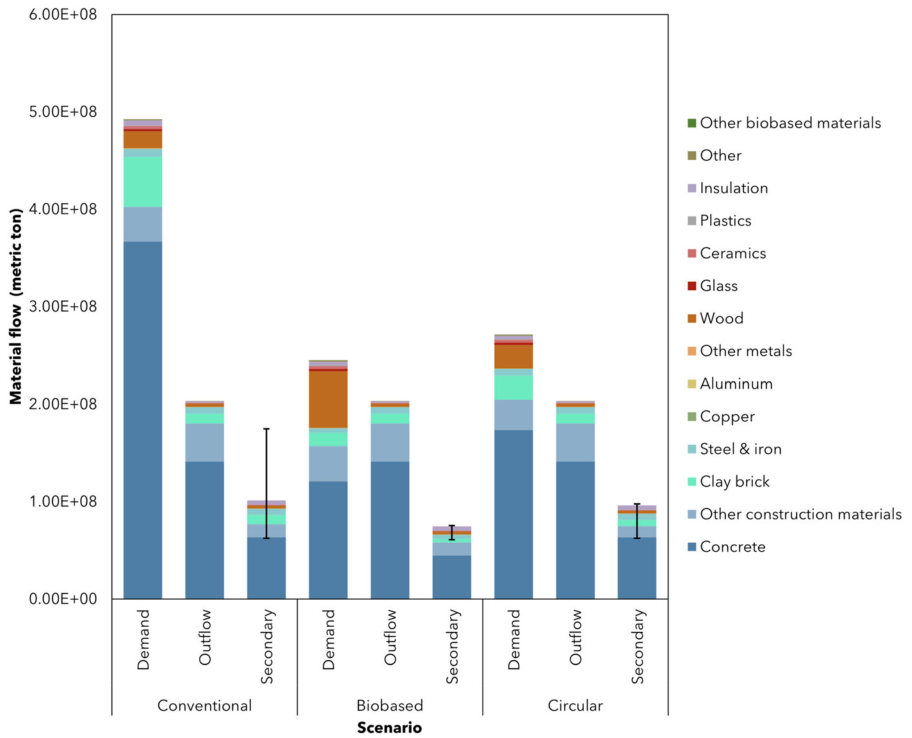


**FIGURE 4** Cumulative material demand for building construction between 2018 and 2050, material outflow from the urban mine, and secondary material share according to current best recycling rate and maximum recycled content. Flows are presented for the three building strategies (pathway Urban). The error bars show the secondary material share for actual recycling rate (RR; lower limit), and for a 100% RR (upper limit). Underlying data for this figure can be found in Supporting Information S3.

dominated by concrete, brick, and other construction materials. Two percent of demand is metals and 4% is biobased materials. Material outflow varies between 2 million ton and 204 million ton. The difference between material inflow and outflow is lower on a material level than in $m^2$ UFA, stemming from a higher mean material intensity of historic buildings compared to modern buildings. Although newly constructed buildings contain more insulation material and glass, the mass of this construction is generally lighter than historic buildings.

Material demand decreases by approximately 50% when shifting from 20% (Conventional) to 80% biobased building structures (Biobased) (Figure 4). The reduction in material demand largely stems from a shift from traditional construction materials such as concrete, clay brick, steel and iron to wood and other biobased materials. Wood demand is approximately three times larger for the Biobased building strategy compared to the Conventional building strategy.

Also the implementation of circular building strategies substantially reduces material demand (Figure 4). In the Circular scenarios, a larger share of material demand consists of other construction materials, steel and iron, insulation, wood, aluminum, plastics than in the Conventional scenarios. The shift is caused by replacement of traditional components, for example, concrete supporting structures, with detachable components, for example, steel supporting structures.

Material outflow between 2018 and 2050 depends on level of urbanization, but not on building strategy. Urbanization leads to higher demolition rates stemming from building densification, but the newly constructed buildings, regardless of the building materials used, will only become available for mining after 2050. Almost 8% of the building stock in 2018 is demolished in pathway Urban, while less than 1% is demolished in pathway Rural. RR and the MRC drastically reduce the reusability of the material outflow. Alternative end-of-life recycling rates (presented by the error bars in Figure 4) are discussed in the sensitivity analysis. Supporting information S2-3 presents an overview of the RR and MRC per material. In scenario Conventional, pathway Urban, 20% of material demand can be met with recycled materials. These values are lower for pathway Connected (11%) and Rural (0%).

The demand and outflow in the Biobased and Circular scenario show a better alignment than the Conventional scenario. In pathway Urban, the outflows present 83% of the material demand in scenario Biobased and 75% of the material demand in scenario Circular. However, only respectively 29% and 34% of the demand in scenario Biobased and Circular can be met with secondary materials. The relatively small potential is caused by limitations in the RR and MRC, and the mismatch between material composition in the material inflow and outflow, especially for scenario Biobased. The recycled content in these scenarios is lower for pathway Connected (between 20% and 22%) and pathway Rural (0%) (see Supporting Information S2-4 for all stock and flow results).

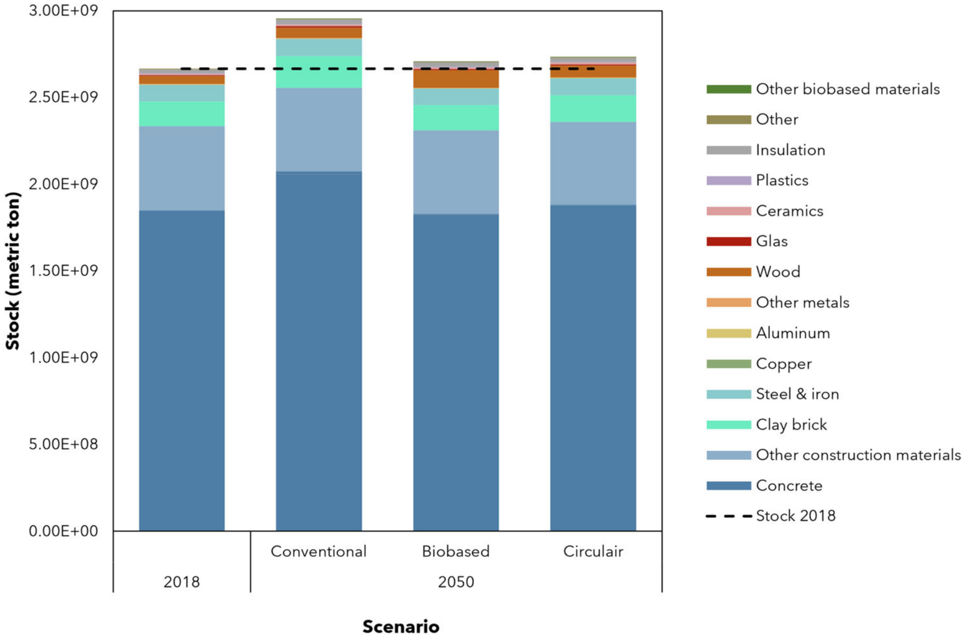


**FIGURE 5** Material stock in Dutch buildings in 2018 and in 2050 for each of the building strategy scenarios (pathway Urban). Underlying data for this figure can be found in Supporting Information S3.

The material stock growth between 2018 and 2050 varies between 11% (Urban) and 18% (Rural) in scenario Conventional (Figure 5). The total material mass encapsulated in buildings comprises between 2.95 and 3.13 billion ton in 2050. Stock growth is lower in scenarios Biobased (between 2% and 9%) and scenarios Circular (between 3% and 11%).

## 3.3 | Spatial analysis of material inflow

We spatially assessed the building construction rates for pathway Urban and Rural. In both pathways, construction activities concentrate in urbanized regions (mainly in the middle-west of the Netherlands), as a result of high projected household growth in these areas. Within these regions, building activities concentrate in more densely built-up areas in pathway Urban, and shift to the municipal outskirts in pathway Rural. Figure 6 presents, as an illustration, the building construction pathways in the municipality of Amsterdam. The historic center of Amsterdam does not qualify for new building activities instead, the focus is on maintaining and upgrading the historical and often centuries old buildings. In Amsterdam, total material demand is 31 million ton in pathway Urban, and 19 million ton in pathway Rural. As the building density is lower in pathway Rural, construction activities mainly take place near or beyond the municipal borders, resulting in a substantially lower material demand within the municipal borders. We refer to Supporting Information S1-2 for more details and the results aggregated to the municipal scale.

## 3.4 | Material related environmental impact

We assessed environmental impacts related to the construction materials in the different scenarios, focusing on GHG emissions and land use. The GHG emissions related to the production of construction materials for scenario Conventional, pathway Urban equals 104 million kilogram $CO_2$ equivalent (Figure 7). In scenarios Biobased and Circular, the global warming potential is reduced with, respectively, 45% and 43% compared to scenario Conventional.

Although the Biobased scenario shows the lowest global warming potential, it is also most land intensive. 92% (scenario Baseline) to 99% (scenario Biobased) of land occupation is associated with wood production (see Supporting Information S2-5 for details). Figure 7 shows the total required surface area of land for the production of wood (for estimated annual wood demand) in pathway Urban for the three materialization scenarios. Approximately 16.300 $km^2$ of land are required for scenario Biobased, equal to 39% of the surface area of the Netherlands. The required area of land is smaller, yet still significant, for scenarios Circular (7.100 $km^2$) and Conventional (4.900 $km^2$).

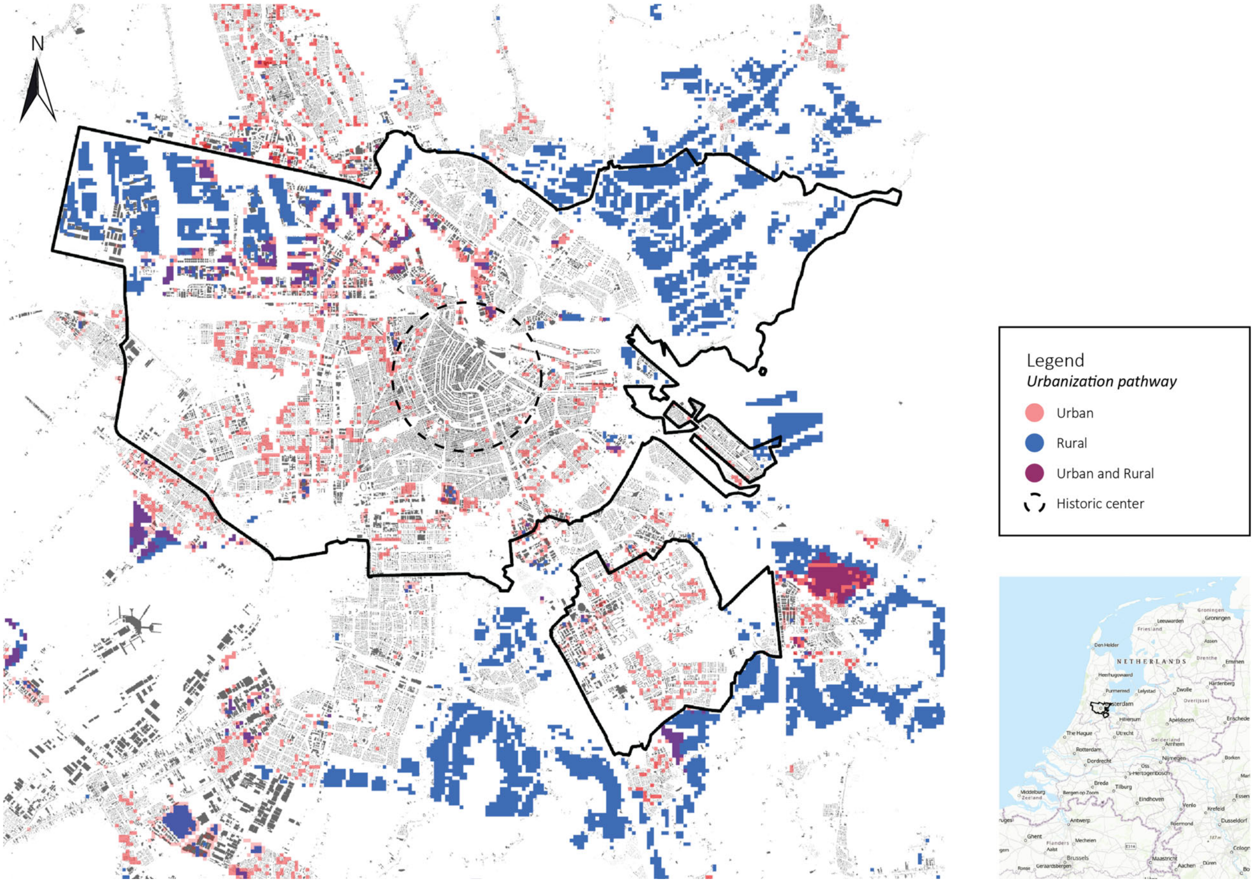


**FIGURE 6** Building construction locations in the municipality of Amsterdam for pathway Urban (pink) and Rural (blue). When scenarios spatially overlap, locations are marked as purple. The black line marks the municipal border

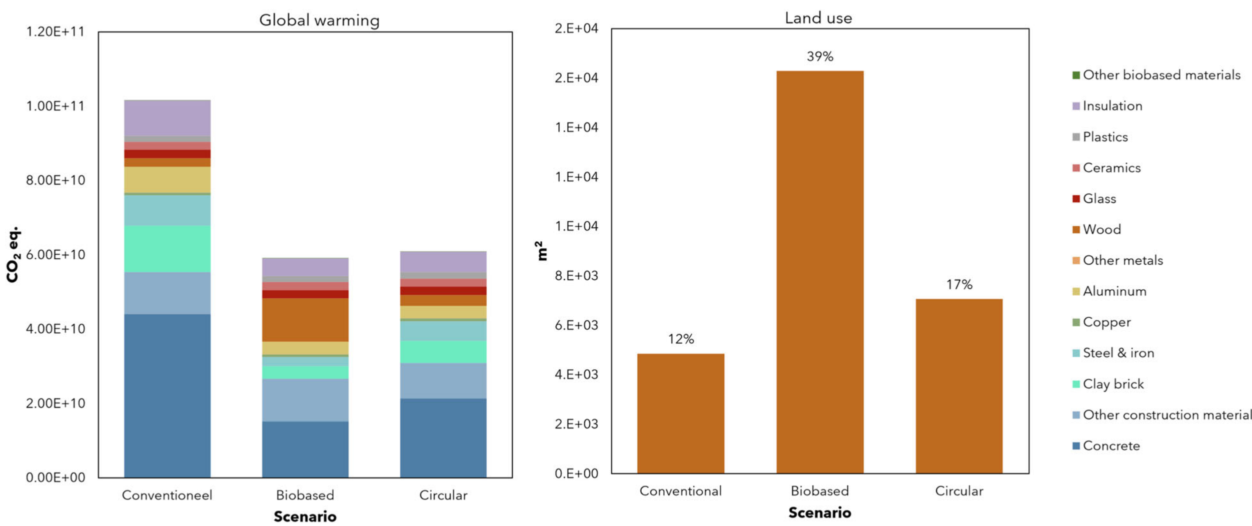


**FIGURE 7** Global warming related to cumulative material production (including the secondary material share) between 2018 and 2050 and land area required for primary wood production. The results are presented for each building strategy scenario (pathway Urban). The data labels in the right figure present the surface area of the Netherlands that would be required for primary wood production. See Supporting Information S1-4 and S2-5 for details. Underlying data for this figure can be found in Supporting Information S3.

## 4 | DISCUSSION AND CONCLUSION

### 4.1 | Main findings of the study

In this study we introduce a novel approach for spatially explicit MFA of building materials. We assess how building strategy scenarios and urbanization pathways affect material stock and flow dynamics in the built environment in the Netherlands. Furthermore, we assessed the potential to close material cycles, and material related GHG emissions and land use.

Compared to space heating in the Netherlands, the mean emissions related to construction materials are modest: 15%. However, in a future where buildings' operational energy is strongly reduced, material related GHG emissions could outweigh use-phase related emissions. Reducing material related emissions is therefore important. We consider two strategies for doing so—substitution of conventional construction materials by biobased materials, and moving toward circular construction—and compare them with a baseline scenario of conventional buildings.

We find that the effects of a transition toward a circular or biobased building sector, even if started right now, will only become apparent well after 2050. Closing material loops in the built environment is limited by continuing stock growth and slow stock renewal. Changes in the building stock are made at slow pace, as materials remain in stock for several decades or even centuries due to the typical long lifespans of Western European buildings (Deetman et al., 2020; Miatto et al., 2019).

Shifting toward biobased materials and circular construction narrows the gap between material demand and outflow. Both building strategies result in a substantially lower primary material demand (reduction of approximately 55% compared to Conventional) and lower the global warming potential related to material production (reduction of approximately 45% compared to Conventional). The circular building strategy also increases reusability of materials or even building components at the end-of-life.

Increasing the share of circular buildings will—as a result of long building lifespans—only yield reusable components and materials after 2050. Building materials that become available in the coming decades are typically not designed for material reuse. Recycling therefore remains a key circularity strategy in the building sector. Our results however reveal limited recovery potential with the current best practice recycling technologies. Investment in recycling technologies therefore presents an important policy priority to reduce primary material demand. However, the strategies will also result in a larger mismatch in material composition of the inflow and outflow, especially for scenario Biobased. This puts limitations to the amount of demolition waste that can actually be recycled. Such a temporary mismatch is inevitable in a transition toward a circular and low-carbon building sector.

Material stock dynamics are also affected by the degree of urbanization, highlighting the relevance of a spatial approach. In our model, urbanization results in higher building replacement rates, but constructed dwellings are typically smaller (mainly apartments) than dwellings constructed in rural areas (mainly detached or row houses). On a spatial scale, construction activities show larger differences. Differences in demolition rates are far larger, being relatively large in pathway Urban, and close to zero in pathway Rural. The results can help policy makers to understand the implications of spatial planning choices on material stock and flow dynamics, and support circular policy at different spatial scales.

We deliberately chose high implementation rates for circular and biobased construction to better understand the effect of policy choices. This results in larger reductions in GHG emissions compared to studies that assume a moderate increase in certain building strategies (Heeren & Hellweg, 2019; Zhong et al., 2021). Our scenarios are based on projections and trends in literature, suggesting that realization of these relatively ambitious building strategies is feasible.

While shifting toward biobased materials lowers material related GHG emissions, the production of these materials is also highly land intensive. In each of the assessed scenarios, land-use demand for wood production requires a land area for forestry that is double the present forested area in the Netherlands. In densely populated countries such as the Netherlands, expanding capacity for forestry will remain limited. Scaling up the share of biobased structures will therefore increase the dependency on imported wood. Whether this would be problematic and to what extent local wood production could be increased needs to be further investigated.

The circular building strategy is most favorable when considering both GHG emissions and the land use related impact. Circular buildings will directly lower GHG emissions as a result of lighter construction, and have a relatively low land area demand. On the longer term, circular buildings can further lower GHG emissions as a result of better reusability of the materials at the buildings' end-of-life. However, we would highlight that reuse at component level may be difficult, or even unwanted for some components, especially load-bearing structures such as steel frames, as they are critical components of the building structure and their quality may not be guaranteed after decades of use (Rakhshan et al., 2020). Such limitations must be considered in the building design phase. Nevertheless, circular building design will still facilitate separation of the building materials, and thus material recycling.

Other measures to reduce emissions could still be assessed, that is, lifetime extension through building renovation, changes in energy mix, increased recovery rates, and increased production efficiency. Moreover, it remains important to put the building related emissions in perspective to other sectors.

The material stock per capita in our study corresponds well with the stock per capita in a Dutch municipality in a study by Verhagen et al. (2021), but also shows significant differences compared to other studies (Table S2 in Supporting Information S1-5). These differences could be explained by a relatively low UFA and material intensity of Dutch buildings.

## 4.2 | Sensitivity analysis

A sensitivity analysis was performed to gain a better understanding of the importance of some of the model assumptions. Three sensitivity variants were defined, one focusing on a change in UFA per dwelling, one presenting a lower population growth and one using different end-of-life recycling rates (RR).

As the majority of the material demand stems from the construction of residential buildings, a reduction of 20% UFA per dwelling significantly reduces material demand: approximately 19%. The total stock declines with a maximum of 3.3% compared to a constant UFA per dwelling. More intensive use of floor space therefore presents an effective measure to increase material circularity and reduce the environmental impact related to primary material production. Reduced UFA may also yield lower use-phase related emissions as a result of lower space heating demand (Pauliuk et al., 2013). While there are developments in the direction of more space per person due to increased income levels and a reduction of the number of people per household, presently we see that the rapidly increased costs of housing may provide an incentive to revert that trend and make a reduction of floor space per capita likely or at least possible. Strategies to reduce the UFA in non-residential buildings could also be investigated, for example, flexible workspaces or stimulation of working from home.

An alternative projection for socio-economic developments, with low economic and population growth (van Eck et al., 2020) results in a large reduction of material demand. This is unsurprising, as population growth directly relates to building demand. Material demand is reduced with approximately 58% in this scenario. Although the reduction in primary material demand supports CE ambitions, the potential to close material cycles remains limited due to low recycling rates and maximum shares of recycled content, again highlighting the need to improve recycling technologies.

Changing the best practice RR to actual RR slightly reduces the recycled content potential in newly constructed buildings (refer to section S2-3 and S2-6 in the Supporting Information for more details). For pathway Urban, the reduction is 8% for scenario Conventional, 5% for scenario Biobased, and 12% for scenario Circular. Increasing the RR to 100% especially affects scenario Conventional. In this scenario, the recycled content potential increases 15% compared to current best recycling rates. A 100% RR hardly changes the recycled content potential for scenario's Biobased and Circular, as the MRC is already almost reached for the best practice RR. The results suggest that with current recycling technologies, a higher level of circularity is already feasible if recycling efforts improve. Further improvement of RR is necessary, together with enhancement of the MRC.

## 4.3 | Limitations and directions for future research

Demolition was modeled as a result of building densification, resulting in nearly zero demolition rates in pathway Rural. This assumption likely presents an underestimation. Demolition of buildings because they no longer conform to standards, or because of wider considerations of spatial planning, are now not included. Integrating these kinds of transformations is on the research agenda, and will be implemented in the current model when possible.

In addition to adding more temporal detail, it would be interesting to extend the analysis beyond 2050, as the potential to close material cycles will remain limited until 2050. Circular buildings constructed in the coming decades will only become available for urban mining in the more distant future. Together with improvements in recycling technologies, the potential to close material cycles will increase.

Values for RR and MRC were based upon national and European statistics and current recycling practices. While these numbers are representative of current handling of construction and demolition waste, they are likely not representative for 2050. We deliberately used current best practices to identify barriers in the transition toward a circular economy. However, recycling practices will likely improve toward 2050, resulting in a higher circularity potential.

In addition to building construction and demolition, significant material flows originate from building (energy) renovation, transformation, and extension. These activities also affect the building lifespan, thus the stock dynamics of the building sector (Lederer et al., 2021). Inclusion of these activities is therefore important. We aim to include these activities in a future study.

## 4.4 | Conclusion

Our results reveal both opportunities and challenges with regard to lowering GHG emissions related to construction materials. Significant emission reductions can be achieved through alternative material use and increased reuse and end-of-life recycling rates. Implementation of circular building strategies directly reduces emissions through lighter construction and facilitates material recycling and reuse at the buildings' end of life. The latter will however only become visible well after 2050, as a result of long building lifespans. Construction of biobased buildings reduces embodied GHG emissions, but side effects can be expected especially due to the significant surface area needed for wood cultivation.

Continuous stock growth, slow stock renewal, and low high-end recycling rates limit the potential to close material cycles. A shift toward biobased and circular buildings and improved recycling efforts reduce the gap between demand and outflow. Other strategies, such as more efficient use of building space and lifetime extension need to be implemented as well.

In addition to building strategy, this study highlights the importance of including the effect of urbanization on building stock dynamics, as it not only affects the location of building construction, but also the size of dwellings and the extent of construction and demolition activities. For example, urbanization leads to both smaller dwellings and higher building replacement rates, which have potentially opposite effects on overall sustainability.

The complex message to society and governments is we cannot expect quick results and need to be on the lookout for side effects, but nevertheless we need to start making changes in construction and demolition methods as soon as possible in order to achieve a low-carbon built environment.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article.

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## SUPPORTING INFORMATION

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

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