



Full length article

Invasive alien plants as an alternative resource for concrete production – multi-scale optimization including carbon compensation, cleared land and saved water runoff in South Africa

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ABSTRACT

Today's cities are ever-growing, especially in the Global South, inducing massive construction activity. To satisfy these needs we need feasible and environmentally sustainable construction materials, the use of local solutions and, if possible, to enable synergies between sectors for maximum environmental benefit.

In South Africa and beyond, invasive alien plants are threatening the indigenous ecosystem while exacerbating water security by affecting water surface runoff and fueling wildfires that release carbon to the atmosphere. The literature suggests that bio-based construction materials can turn buildings into carbon pools. However, the dynamics of using bio-based materials at the urban scale are not yet well known. This paper tests a new type of non-structural bio-concrete, using invasive alien wood chips as a substitute for sand and gravel as aggregates, for future residential construction in Cape Town, comparing this new material to conventional and to earth-based materials, and benchmarking different policy scenarios. Firstly, the material is optimized within technical possibilities achieving the capture of 897 kg of CO₂ equivalents per m³. Secondly, a reverse-engineered approach is employed to uncover the limitations of the material. Additionally, CO₂ emissions from cradle to gate and additional land and water use benefits are analyzed, considering spatial dynamics for transportation impacts.

The optimized mix design using invasive alien plants as an alternative resource, combined with a policy that promotes multi-story buildings, offers great potential to achieve near carbon neutral cities, clearing land of invasive alien plants and thus saving annual water surface runoff.

1. Introduction

Cities are growing in both size and number around the globe but most of the world's fastest growing cities are in Africa and Asia (UN,

2018). Urbanization, enabled by rapid economic development, is accelerating large building activity in developing countries (IPCC, 2015). Yet, circa one-third of the urban population in developing countries in 2010 did not have access to adequate housing (UN

Abbreviations: ALCA, Attributional LCA; BAU, Business as usual; BIC, Biomass-insulated concrete; CLCA, Consequential LCA; CO₂, Carbon dioxide; eq., Equivalents; GHG, Greenhouse gas emissions; GWP, Global Warming Potential; IAP, Invasive alien plant; LC, Life Cycle; LCA, Life Cycle Assessment; MFA, Material Flow Analysis; OPC, Ordinary Portland cement; PCFA, Per capita floor area; SI, Supplementary Information; tons, Metric tons; RDP, South African research and development program; UM, Urban Metabolism; VAI, Value Added Industries program from the South African Department of Environmental Affairs; VAP, Value added product.

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HABITAT, 2010).

The 2030 Agenda for Sustainable Development, specifically the Sustainable Development Goal 11, aims at making cities and human settlements inclusive, safe, resilient and sustainable (UN, 2019). To do so, we need to provide sustainable and adequate housing for all. One priority to achieve a low carbon building sector is to reduce the embodied emissions and energy of construction materials (due to mining, manufacturing, processing, and transportation) (UN Environment and International Energy Agency, 2017). Thus, we need construction materials that are locally available for large-scale construction, that enable adequate housing, and that have low embodied impact.

The most common man-made material today is concrete (De Brito and Saikia, 2013). It has been considered cheap, reliable, and simple to build with for a long time (Simpson, 1989). Yet, cement, a component of concrete, is usually made with energy-intensive clinker. Moreover, the natural aggregates sand and gravel can become scarce at high demand rates (Ioannidou et al., 2017) and their depletion is destroying landscapes (Cousins, 2019). During recent years, various authors have suggested that bio-based construction materials might be environmentally friendly and suitable alternatives to conventionally used materials (García-Pérez et al., 2018; Heidari et al., 2019; Pittau et al., 2018; Sinka et al., 2018). Even though there are concerns regarding their durability due to animal and insect harms, as well as creation of mold (Binici et al., 2016), bio-based materials are intrinsically low-energy, (partly) natural and, if managed correctly, from a renewable source (Heidari et al., 2019). There are many examples of bio-based materials used in construction: structural timber (Hafner and Schäfer, 2017; Li et al., 2019), wheat straw (Gallegos-Ortega et al., 2017) or rice straw bales (Marques et al., 2019), thermal retrofit solutions based on cork (Silvestre et al., 2019, 2016) or on hemp fibers (Sassoni et al., 2014), traditionally used materials that are enhanced with a bio-component, such as bio-concrete made with bamboo waste (Caldas et al., 2019), or fired clay bricks with wheat straw and olive stone flour as additives (Bories et al., 2016). The possibilities are sheer endless.

An important benefit of bio-based construction materials is that during the plant's growth biogenic carbon is captured, which remains stored in its biomass when used in construction (Attia, 2016). The carbon storage of bio-based construction materials in buildings is, however, only temporary (Pittau et al., 2019) and finishes at the end of life (EoL) of the building, assuming that the bio-based material is incinerated and the carbon released back to the atmosphere (Heeren and Hellweg, 2019). Net benefits of biogenic carbon storage is subject to an ongoing scientific discussions (Cherubini et al., 2016; Demertzi et al., 2018; Gustavsson et al., 2017; Silvestre et al., 2016), leaving it unclear if and how to account for it. The hope is that through the creation of buildings as carbon pools, storing biomass and therefore carbon, the built environment can become carbon neutral, meaning that through the storage of biogenic carbon in buildings the embodied GHG emissions of construction materials can be compensated (Pittau et al., 2018). At the building scale, results for bio-based construction are mostly promising, as shown for high-rise timber buildings that potentially reduce climate change impacts by 84% (Skullestad et al., 2016). Yet at a larger scale, conclusions do not always suggest clear pathways and mostly focus on timber construction: Stocchero et al. (2017) analyzed large-scale timber construction in Auckland, New Zealand and concluded that such strategy could help achieve the city's carbon reduction target faster. Churkina et al. (2020) recently analyzed the potential benefits of mass timber construction at the global scale, concluding that annually 0.01–0.68 GtC/y could be stored in new urban construction. The authors emphasized the importance of a prolonged lifetime of the transitioned biomass on land. Heeren and Hellweg (2019) however, analyzed the potential of wood-based construction in Switzerland and found that the cumulated GHG emissions are only slightly reduced compared to a business as usual scenario. Pittau et al. (2019) added to those findings with a transnational study that suggested fast-growing bio-based materials, such as hemp and straw, are a more promising alternative than timber to act as a

carbon sink. The different conclusions are surely based on varying model parameters, but many questions related to bio-based construction simply remain unanswered, and not only regarding how to account for biogenic carbon.

Pittau et al. (2019) are among the few authors that analyzed the use of bio-based construction materials at a large scale and considered the supply of material to estimate the potential carbon storage, as well as the feasibility of its implementation. However, there is little knowledge on the interaction between built environment and natural supply of biomass for construction material. Most authors neglect questions regarding the use of land and land requirements for the cultivation of biomass, when studying carbon storage potential of bio-based construction. Accommodating the present wave of urbanization will require massive amounts of construction materials (UNEP, 2013), even if based on bio-based construction. This means that we must either secure a renewable source, for example through sustainable forest management in the case of wood construction or find opportunities for synergies between the goals of the construction sector and others. The choice of material should consider a holistic point of view, especially when it is bio-based, to ensure that the material is used efficiently and that new solutions will be used in practice. Only then we can understand if bio-based construction is a realistic pathway to a carbon neutral building stock.

A recent effort by scientists belonging to the "Value Added Industries" (VAI) program from the South African Department of Environment, 2019 yielded a new type of biomass-insulated concrete (hereafter referred to as BIC) that is made with wood-chips aggregate sourced from invasive alien plants (IAP). By using IAP in construction, the invasive biomass is removed from the ecosystem. The new material could be used for structural and non-structural elements. It also shows promising results regarding mechanical and fire resistance performance. However, the cement content of the proposed mix design needs to be reduced and the biomass content increased to minimize material production impacts. Moreover, the VAI group developed a new housing type, named *lighthouse*, which is a proposal to offer a more sustainable alternative to the government subsidized housing buildings from the reconstruction and development program (RDP). It refers to a single and multi-level residential concrete building built with BIC. RDP houses, as they have become commonly known, can be found across most of the defined building typologies according to the South African census (Statistics South Africa, 2011). They are often inadequate regarding housing material and design (Manomano et al., 2016). An improved housing typology is needed to meet the promises made by the South African government after the end of apartheid to tackle former injustice by providing housing for all. The *lighthouse* prototype is an effort in that effect, which also aims at creating localized job opportunities through the harvesting of IAP species and the development of low-tech, labor-intensive construction practices for local communities (refer to Supplementary Information (SI) I). Using local materials is important to increase the sustainability of national social housing projects, as was shown for the case of Brazil (Giannetti et al., 2018).

2. Method and data

2.1. Goal and scope

The present study focuses on the reduction of embodied GHG emissions and on the implementation of the new type of BIC (developed by the VAI program) in residential construction for the specific African context. The two research goals are as follows:

- (1) The analysis of the future material requirements and embodied GHG emissions of residential construction in an African city, comparing different policy and material scenarios, including a bio-based one with BIC;

- (2) The application of a system approach for a multi-scale optimization of BIC, considering factors that go beyond the boundaries of the building stock including the local availability of biomass.

2.2. Framework

Fig. 1 shows the framework of the model. To achieve research goal (1) a top-down demand-driven building stock model is employed, which was originally proposed by Müller (2006) and later adapted by Göswein et al. (2018) to consider multiple building typologies and materials in a South African context. The latter is also used here and again a South African city is chosen as a case study (refer to Section 2.3). The model requires Material Flow Analysis (MFA), which is a “systematic assessment of the flows and stocks of materials within a system defined in space and time” (Brunner and Rechberger, 2004).

The building stock model is depicted on the left side (purple) of Fig. 1. Rectangles stand for processes, ovals for flows, and (layered) hexagons for drivers and determinants (per building typology). Influences between variables are visualized through dashed lines. A stands for the floor area stock, M for the materials stock, and C for accumulated embodied carbon related to construction. The net stock accumulation is measured in tons of materials and denoted by dA/dt and dM/dt , with dA_{in}/dt and dM_{in}/dt for input flows (new construction), and dA_{out}/dt and dM_{out}/dt for output flows (demolition of buildings). The main drivers of the model are population growth (P) and the per capita floor area as a lifestyle indicator ($PCFA$). Additional drivers are: the service life of building typologies (estimated through log-normal distributions); material density per type of material and building element (M_A); and embodied GHG emissions per type of material.

These impacts include the Life Cycle (LC) stages A1 “raw material supply”, A2 “transportation of raw material to manufacturer” and A3 “manufacturing” as defined in EN15804:2012 (CEN, 2012). Moreover, the carbon storage of biomass is considered, which is explained in more detail in Section 2.3. For the urban scale analysis also LC stage A4 “transportation to construction site” is considered. LC stage A5

“construction/installation” is not considered due to a lack of reliable data. Different data sources are used. The GWP for the different LC stages was calculated with SimaPro v9 using the IPCC 100a method (2013). Additional information for different raw materials of concrete production and for the mixing of concrete were taken from Kurda, (2017) and Kurda et al. (2018a). All data sources and the exact values for GWP are listed in SI II. Due to a lack of data for South Africa, most of the LCI is from Europe but is adapted for South Africa, e.g. through the electricity mix used, whenever possible. Other indicators such as particulate matter, acidification potential and loss of biodiversity are not analyzed in the present study.

Only residential buildings are considered in this study since the construction of new dwellings in countries of the developing world can be forecasted based on the evolution of P and $PCFA$ as was shown by Hu et al. (2010) for Beijing, while infrastructure development is related to the density of urban fabric, for which a bottom-up building stock model would be required (Lanau et al., 2019). The characteristics of the following typologies, based on Statistics South Africa (2011), are analyzed: house on a separate stand; flat in a block of flats; informal dwelling in backyard; and informal dwelling in settlement. Additionally, the *lighthouse* typology is analyzed. The analyzed conventional materials are: concrete; steel; fired clay; timber; corrugated iron. The alternative materials are: unstabilized earth; and the new type of BIC as described in the introduction. Even though the focus of this study is on BIC, unstabilized earth is included as a comparison since it was shown for a similar context that earthen construction allows a drastic reduction of embodied GHG emissions (Göswein et al., 2018). The studied time horizon is from now until 2050 and one-year time steps are analyzed. The model starts in 1975. The latest available census data is from 2011, which is assumed to be the present situation. From 2011 until 2050 material requirements are forecasted for different policy and material scenarios, as described in Section 2.3. The output of the model are material quantities over time and the associated embodied GHG emissions. At this stage, the BIC design mix is assumed fixed.

To achieve research goal (2) a reverse engineering systems approach

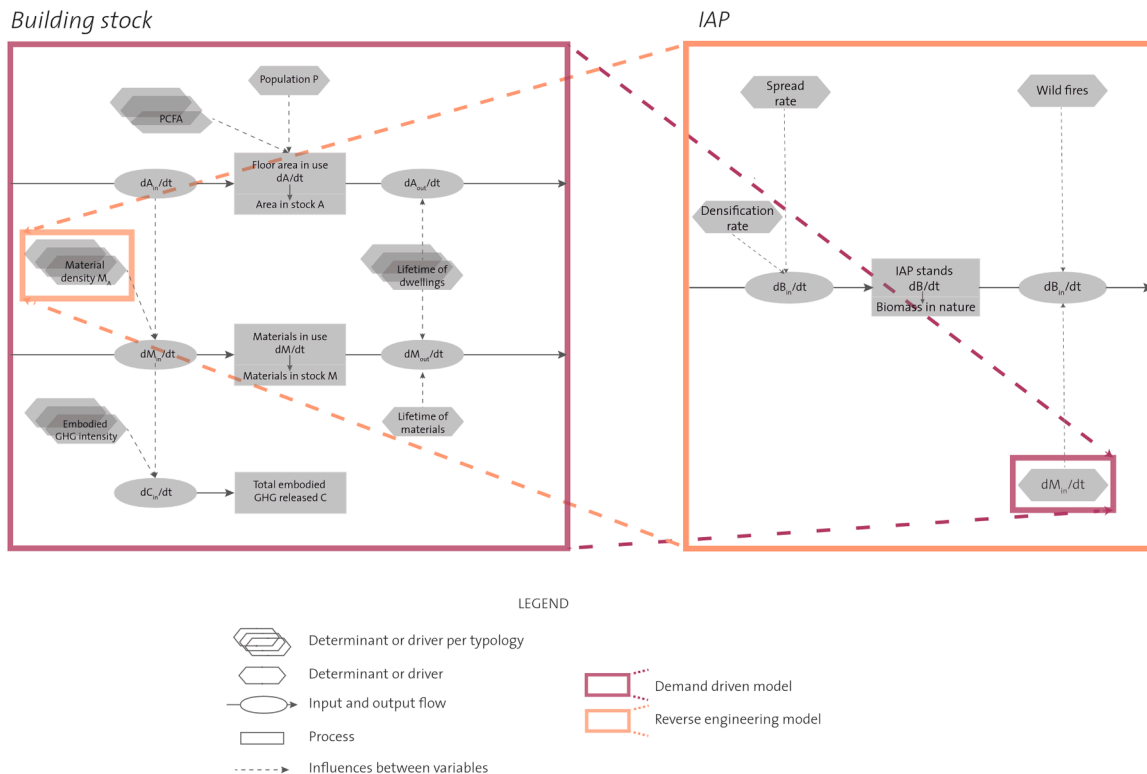


Fig. 1. Framework of the study. PCFA stands for per capita floor area, A for area, M for materials, C for embodied GHG emissions, B for biomass.

is employed. Now, it is assumed that there is a certain flexibility of the BIC design mix since the material is still in the development phase. Two perspectives are employed: an optimization of the BIC at the material scale versus an optimization of the BIC based on the results for embodied GHG emissions from the building stock model in (1). The optimization of BIC is aiming at carbon neutrality and the two optimization perspectives are based on different declared units, which is in line with the respective scale of analysis:

- To achieve carbon neutrality at the material scale, the current BIC design mix including biomass content is optimized. This considers technical limitations. The aim is that the biogenic carbon that is stored as an aggregate for BIC, instead of being burned, can offset the GHG emissions from cradle to gate for the declared unit: 1 m³ of BIC;
- To achieve carbon neutrality at the urban scale, the building stock model from (1) is reverted, with the amount of biomass in BIC as the variable, to analyze how much biomass needs to be incorporated in the BIC mix to offset the GHG emissions for the declared unit of the yearly required building materials for new residential construction at the urban scale as obtained in (1). This is illustrated through the orange highlights in Fig. 1. In this step, the avoided emissions of burning biomass (see Section 2.3), considering the lifetime probability of buildings and of trees, are accounted for as “carbon negative”. This entails that the biomass needs to offset not only the impacts from its “host”, i.e. BIC, but also from all other materials (i.e. steel, fired clay, timber and corrugated iron). The transportation distances per raw material for LC stage A2 are estimated. A sensitivity analysis of the transport-related impacts of sourcing the biomass can be found in SI III.

Furthermore, the amount of required and available IAP biomass is analyzed regarding land that is currently invaded with IAP and that could be cleared, and the potential benefits on water surface runoff savings. Yet, these impacts are presented separately from the embodied GHG emissions of construction materials. The systems approach helps to benchmark and optimize bio-based materials, which is interesting to material scientists, civil engineers and urban planners.

2.3. Case study

The methodology is tested for Cape Town, the second biggest city in South Africa. Cape Town has been in the spotlight of different Urban Metabolism (UM) studies (Currie et al., 2015; Gasson, 2002; Hoekman and von Blottnitz, 2017; Smit et al., 2019, 2017; Strydom et al., 2020), which makes it a well-suited testing ground for a new technology for improved material flows and therefore carbon balance.

South Africa has been struggling with water scarcity for years, bringing Cape Town to the brink of collapse in 2018 (Onishi and Sengupta 2018). IAPs, such as eucalyptus, are exacerbating water security by reducing flows of naturalized mean annual water runoff (Le Maitre et al. 2016) and are particularly prone to wildfires, releasing carbon to the atmosphere (Poona 2008). Species such as Australian *Acacias*, were originally introduced to South Africa to provide ecological services such as wind breaks and providing fuel. However, their detrimental effects on water flows and on the endemic flora and fauna were soon recognized and the costs associated to the control and clearing of IAPs are significant (Vundla et al., 2016). In Cape Town, the most prominent IAP species are *Acacia saligna*, *Acacia cyclops*, and *Pinus* species. Across the country the distribution of species is different but the most frequent are *Acacia sl.*, *Eucalyptus*, *Pinus*, *Chromolaena odorata*, and *Opuntia* species (Kotzé et al., 2010). A map in the SI IV highlights the extension of invaded land in South Africa. Natural grassland and natural wooded land are at risk of becoming invaded as well. The problem is not unique to South Africa. Also Kenya, Ethiopia and Tanzania are fighting the invasion of alien *Prosopis* trees that affect ecosystems and livelihoods as well as worsen water availability (Shiferaw et al., 2019a, 2019c, 2019b).

Outside the African continent, New Zealand (Harding, 2001), Australia and Chile (Richardson and Rejmánek, 2004) have been fighting the invasion of wilding conifers as invasive weeds for years. Creating synergies to make use of the invasive biomass in value-added products (VAP) can help to accelerate the eradication of these pests (Mugido et al., 2014). Besides construction materials, other VAP made with IAP are charcoal, firewood, paper, and tanning agents used for the production of leather (Vundla et al., 2016). However, these products have short life spans and therefore lead to an emission of biogenic carbon within a shorter period of time compared to using IAP biomass for building construction.

In general, the analysis of the storage of biogenic carbon dioxide (CO₂) of harvested biomass in the built environment is dependent on the rotational and anthropogenic storage periods of the biomass (Guest et al., 2013). However, for the case study of IAP in South Africa, the parameters need to reflect the goal to eliminate IAP and therefore not to regrow IAP after felling them. Furthermore, as a simplification the model assumes no plantation of other (native) tree species subsequent to the IAP felling. In reality, it is recommendable to fill the vegetative void after the eradication of IAP, not only to store biogenic carbon but also to rehabilitate the native ecosystem and to avoid erosion and the infestation of new pests. The analysis of landscape management is out of scope here but Shiferaw et al. (2019b) gives recommendations on this matter. For simplification, the present paper does not analyze the amount of biogenic CO₂ stored, but instead the avoided emissions from burning of IAP biomass, because in this specific case it is aimed to eradicate the IAP stands, in contrast to a sustainably managed forest that would allow for accounting of stored biogenic CO₂. According to the EN 16,449 (CEN, 2014), the carbon content of any wood is 50%, by weight. This means that 1 kg of IAP biomass refers to 0.5 kg C and, if used in construction, it is assumed that this refers to 1.83 kg of avoided CO₂. Black carbon emissions are not considered.

The avoided emissions of not burning biomass in fires are analyzed for the biomass component of BIC in the bio-based material scenario. In nature, in South Africa, circa every 15 years the IAP burn due to wild fires (Le Maitre et al., 1996; van Wilgen, 1996). It needs to be noted that this parameter directly influences the carbon credit calculations. Even though it underlays uncertainty, it is assumed constant here. Also, it is specific to the region. When using BIC in buildings the biomass is stored for an extended period of time (difference between the building's lifetime that was constructed with a bio-based material, and the natural occurrence of wild fires). This effect was demonstrated for bamboo construction by Zea Escamilla et al. (2016). As so, for the present study, in 2050 only the BIC of buildings that are older than 15 years (corresponding to the wild fire cycle), was accounted for the avoided emissions of not burning biomass. Buildings' lifetime corresponds to different log-normal distributions for the different building typologies. The present study considers material incineration at the building's EoL, thus not accounting for the embodied biogenic carbon. Instead, avoided emissions of burning biomass are calculated based on a consequential LCA (CLCA) approach. CLCA is strong in mapping impacts of indirectly affected processes of a decision and to include the impacts of systems affected by the change in demand of the functional unit (Guinée et al., 2011). The results for avoided emissions are compared to those obtained with attributional LCA (ALCA).

Furthermore, the carbon sequestration of the construction material timber, mostly used for roof constructions of the different building typologies, is credited in this study. The carbon sequestered in 1 m³ of softwood with a dry density of 434 kg/m³ at manufacturing gate corresponds to 794.88 kg CO₂ eq. (American Wood Council and Canadian Wood Council, 2013).

Three policy scenarios, which refer to changing shares of dwelling types, are defined as: “business as usual” (BAU); “replace the RDP houses with the improved *lighthouse* typology”; “promote flats in multi-story buildings”. They can be found in SI II along with all other model input parameters. Three construction material scenarios are defined to reflect

a “business as usual”, “bio-based construction with BIC”, which replaces non-structural concrete with BIC used in building elements, and “earth-based construction”, which replaces non-structural concrete and fired clay with unstabilized earth. Their quantitative description as well as the definition of the building typologies can be found in SI II. They are based on Göswein et al. (2018).

3. Results and discussion

The results are organized in two parts: firstly, the embodied GHG emissions for Cape Town’s residential building stock based on the demand-driven model are presented. The second part focuses on the reverse-engineered optimization of the proposed BIC across scales, considering carbon storage, cleared land due to felling of IAP trees, and water surface runoff savings.

3.1. Building stock demand

This section presents the results for research goal (1). Three policy and material scenarios are analyzed for the present situation and potential future evolution. Fig. 2 shows the emissions for all construction materials embodied in the residential building stock for the present situation (based on census data from 2011) and a forecast for 2050. The striped bars in Fig. 2 show the results of the CLCA regarding the avoided emissions of burning biomass. The solid bars show the results of the ALCA, from cradle to gate for all construction materials under study, and including, for the construction material timber, also the carbon sequestration.

The embodied emission today is 3.09×10^7 tons CO₂ eq. while it might increase to 6.87×10^7 tons CO₂ eq. in 2050 considering a business as usual practice for policy and materials. The two alternative policy scenarios, to replace the existing RDP housing typology with the more adequate *lighthouse* typology and to promote flats in multi-story buildings, have comparably even higher impacts for the BAU material scenario. This is because both, the substitution of RDP houses with the *lighthouse* typology and the shift in typologies from free standing houses to multistory buildings, as modeled with the materials used in the policy to promote flats, are more material intense. The two alternative policy

scenarios only unfold their potential when combined with alternative materials. Only a combination of the earth-based material scenario with a policy to promote flats enables embodied GHG emissions in 2050 that stay within the range of the present value 3.09×10^7 tons CO₂ eq. Unstabilized earth is mostly used in vernacular architecture. However, its potential for sustainable construction thanks to its availability and low-carbon profile is significant. It can be used to substitute conventional construction materials, such as concrete and fired clay bricks, with non-structural purposes, which make up a significant amount of the building typologies “freestanding house” and “flat” and contribute to these typologies emission profiles (see SI II). Moreover, the values presented here assume that the use of earth is combined with an optimized structure to build vaulted ceilings and save material. The relative savings potential of the bio-based material scenario compared to the BAU material scenario is mainly based on the intensive use of BIC in the formal building typologies. The lowest value within the bio-based material scenario, 4.35×10^7 tons CO₂ eq., is obtained in combination with a policy to promote blocks of flats. If this value is summed with the avoided emissions of burning biomass, -1.99×10^7 tons CO₂ eq., a total of 2.35×10^7 tons CO₂ eq. can be achieved, which makes this solution not only competitive with the earth-based material scenario, but also allows to reduce the total emissions in 2050 compared to today. The policy scenario that replaces the existing inadequate RDP houses with the *lighthouse* typologies yields 5.49×10^7 tons CO₂ eq. for embodied GHG emissions and an additional -2.20×10^7 tons CO₂ eq. of avoided emissions of burning biomass. It is interesting to note that building typologies that represent “heavy” construction and therefore lead to relative higher embodied GHG emissions, also lead to a higher potential of avoided emissions. This is because the more BIC is used the higher the carbon storage potential. The GWP for all material and policy scenarios throughout the studied time horizon can be found in SI V.

3.2. Reverse engineering – becoming carbon neutral

This section presents the results for research goal (2). There are two perspectives that can be considered for the optimization of BIC for this study’s purpose and to answer the research question of how to achieve a climate neutral building stock with bio-based construction materials. On the one hand, there is the classic approach of material scientists to optimize a concrete mix design fulfilling specific criteria, for example for compressive strength and workability, to ensure the new optimized material is appropriate for use in construction. On the other hand, there is the reverse engineering perspective that theoretically analyzes how much carbon needs to be captured in the biomass component of the concrete to achieve carbon neutrality. Since the analysis of the current BIC mix showed that its carbon savings potential is relatively small, the following analysis starts with the optimization of the material and then focuses on the reverse engineering perspective, first at the material, and then at the urban scale, to maximize the carbon storage potential of the mix design.

3.2.1. Optimization at the material scale

The current BIC mix design incorporates 62% Vol. of biomass. Even though this results in a negative GWP (-415 kg CO₂ eq. per m³), the current BIC mix (see Table 1) contains a significant amount of ordinary Portland cement (OPC) and lime (together representing 273 kg per 1 m³ of BIC). This leads to higher embodied GHG emissions of this mix design. Since the material will be used for non-structural purposes, it is, therefore, not necessary to include that much binder. At the same time, the current BIC mix does not reach the full potential of biomass incorporation from a technical point of view.

Thus, the first step of optimization is to substitute the additional binder (lime) with fly ash, a coal-combustion product with pozzolanic properties and an efficient supplementary cementitious material to reduce CO₂ emissions (Kurda et al., 2018b). It needs to be noted that a 60% replacement of OPC with fly ash leads to a 36% reduction of

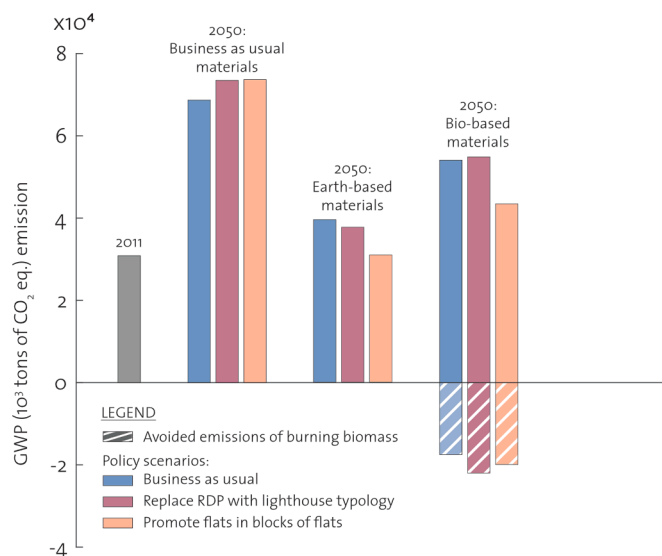


Fig. 2. Annual emission for all materials. The figure compares three different policy scenarios (in color) with three technology scenarios for materials (in grouped bars). Positive impacts refer to the total embodied GHG emissions of all construction materials, from cradle to gate, of the entire residential building stock. The avoided emissions of not burning trees, which are derived from the biomass-content of BIC are disclosed separately as negative emissions.

Table 1
Mix design for 1 m³ of current and optimized BIC mix design.

Material	Current design mix	Optimized design mix with high-performance cement paste
Invasive alien biomass [dm ³]	597	800
Water-to-binder ratio	0.61	0.30
GWP [kg CO ₂ eq. per m ³ excl. biomass]	241	98
Avoided emission [kg of CO ₂ eq. per m ³]	−656	−897

*Refers to impact per kg of material for the LC stages A1 and A3. They are taken from Kurad et al. (2017), except for the GWP coefficient of invasive alien biomass that refers to the carbon content of wood.

compressive strength of the concrete mix (Kurad et al., 2017), which is acceptable for non-structural concrete. By changing any element of the concrete mix, the quantities of the remaining raw materials, cement, its substitute coal fly ash, other types of binder (lime), fine aggregates, and water, also need to be adjusted. The optimization of mixes here replaces 50% to 60% of OPC with fly ash.

As a next step, the paste (sum of binders and water) is reduced while keeping the water-to-binder and water-to-cement ratios constant, which are indicators for the strength development of concrete, which can be expected to be low due to the reduced amount of binder. To improve the strength, a further optimization with a high-performance cement paste through a reduced water-binder-ratio is proposed. Yet, a low water-binder-ratio makes the concrete mixture difficult to handle, which can be counteracted through the use of a superplasticizer. Yet, the induced loss of workability is not relevant for this application since the BIC is designed to be poured and vibrated by hand.

Fig. 3 compares the current mix design with the optimized high-performance concrete (in orange), in relation to its GWP (life cycle (LC) stages A1 and A3) for variable amounts of biomass. For the concrete production process mixing a GWP coefficient of 4.65 kg CO₂ eq. per m³ of concrete is assumed. The optimized concrete mix design is carbon neutral at the material scale with a relatively small incorporation of biomass (33% Vol.). This is because, as referred above, the biomass consists of approximately 0.5 kg of C per kg of wood, which is equal to 1.832 kg of CO₂ eq. per kg of wood and which refers here to the static calculation of avoided emissions of not burning biomass. By comparison, the GWP coefficient used for OPC is 0.898 kg of CO₂ per kg.

Nevertheless, one can estimate that a maximum packing fraction of biomass can be close to 80% Vol due to the aspect ratio of biomass fibers (Martinie et al., 2010). Wood chips allow for a slightly better packing than gravel. For gravel with lower aspect ratio than biomass aggregates, a packing fraction of around 70–80% Vol. can be established (de Larrard and Sedran, 1994). This leads to the optimized BIC mixes as highlighted in Fig. 3 through the intersection with the dashed line and which is detailed in Table 1.

3.2.2. Analyzing the optimized BIC mix at the city scale

On a long time scale a plant's life cycle is considered carbon neutral since the CO₂ that is captured during its growth is released back to the atmosphere.¹ When shifting the system boundaries to the material scale, we could show above that by using biomass in BIC it is possible to become carbon negative at the material scale. The next step is to analyze how to achieve a carbon neutral building stock by 2050. To achieve this,

¹ Please note that when biomass is burned and not replaced soon after, then CO₂ is added to the atmosphere and the plant's carbon cycle should not be considered neutral. Moreover, recent methodological developments have shown that the timing of emissions should be considered for a rigorous carbon cycle analysis. Please refer to Andreae (1991) and Levasseur et al. (2010) for more information.

avoided emissions of burning the invasive biomass content of BIC need to offset the impacts of all the considered construction materials, pre-conditioned that the CLCA methodology is applied. The contribution of the different construction materials to the total embodied GHG emissions of the building stock varies depending on the policy and the BIC design mix.

As explained in Section 2.1, the results for GWP refer to different declared units and LC stages. This section presents the consequences of using BIC, in its current design mix and with the proposed optimization, for new construction of Cape Town's residential building stock. Fig. 4 compares the bio-based material scenario using the current BIC mix, with the proposed optimized BIC mix, regarding the annual GHG emissions in 2050 of the entire residential building stock. The most promising scenario combination is the one with the optimized mix and the policy scenario to promote flats, resulting in 3.74×10^7 tons of CO₂ eq. and additional -3.46×10^7 tons of CO₂ eq. avoided emissions from biomass. This equals a 88% reduction of total GHG emissions (sum of embodied and avoided emissions), resulting in 0.28×10^7 tons of CO₂ eq., compared to the bio-based material scenario with the current BIC mix design for the same policy scenario (promote flats), 2.35×10^7 tons of CO₂ eq. Comparing the lowest value that was achieved with the optimized BIC mix, with the minimum value (3.42×10^7 tons of CO₂ eq. for earth-based materials and a promotion of flats) and the BAU value (6.87×10^7 tons of CO₂ eq. BAU policy and material scenarios) (shown as dashed lines in Fig. 4, values taken from Fig. 2), it becomes clear that using BIC at the urban scale is competitive with using earth-based scenarios. Even more so when the avoided emissions of burning biomass are considered, which leads to the total of 0.28×10^7 tons of CO₂ eq. (sum of embodied and avoided emissions). This extreme low result is very promising regarding overall carbon neutrality of the building stock, especially considering that it is achieved with a bio-based concrete. Constructing with earth, even though possible from a technical point of view, requires a drastic rethinking on how people want to build their houses. Concrete however, is considered cheap, reliable and easy to build with. Therefore, adapting concrete to become more environmentally friendly seems more realistic than a wide application of earth construction.

3.2.3. Biomass incorporation ratio in BIC to achieve a carbon neutral city

To achieve a carbon neutral city by only changing one parameter, the biomass content of BIC, we analyze how much invasive wood chips per m³ of BIC are needed to offset the cradle to gate impacts, referring to LC stages A1, A2 and A3 (Braga et al., 2017), of the other BIC raw materials and mixing, and of the other construction materials (steel, fired clay, timber, and corrugated iron). The impact of LC stage A2 "transportation of raw material to manufacturer" is discussed in more detail later. In this section, fixed values from source of raw material to manufacturer are assumed based on recommendations given by Zea Escamilla and Habert, (2017) (see SI III). The reverse-engineering method proceeds as follows to analyze the biomass content of a BIC mix design to achieve carbon neutrality: firstly, the embodied GHG of steel, clay, timber, corrugated iron of Cape Town's residential building stock are analyzed. Secondly, these impacts are translated into amount of biomass needed to offset them, using the carbon content coefficient of dry wood (CEN, 2014). Thirdly, the reverse-engineering approach is applied dividing the amount of required biomass by total required concrete to satisfy Cape Town's construction needs until 2050.

Table 2 shows the required amount of biomass per m³ of BIC to offset the cradle to gate impacts for the three policy scenarios. Only when the values comply with the maximum packing of biomass (80% volume, corresponding to 480 kg biomass per m³ of concrete assuming a density of 600 kg/m³ for the invasive wood chips) they are realistic and possible from a technical point of view. The results in Table 2 show that it is not possible to optimize BIC so that the biomass content of the material, when used in city wide construction, can offset the cradle to gate impacts of the all construction materials to achieve a carbon neutral

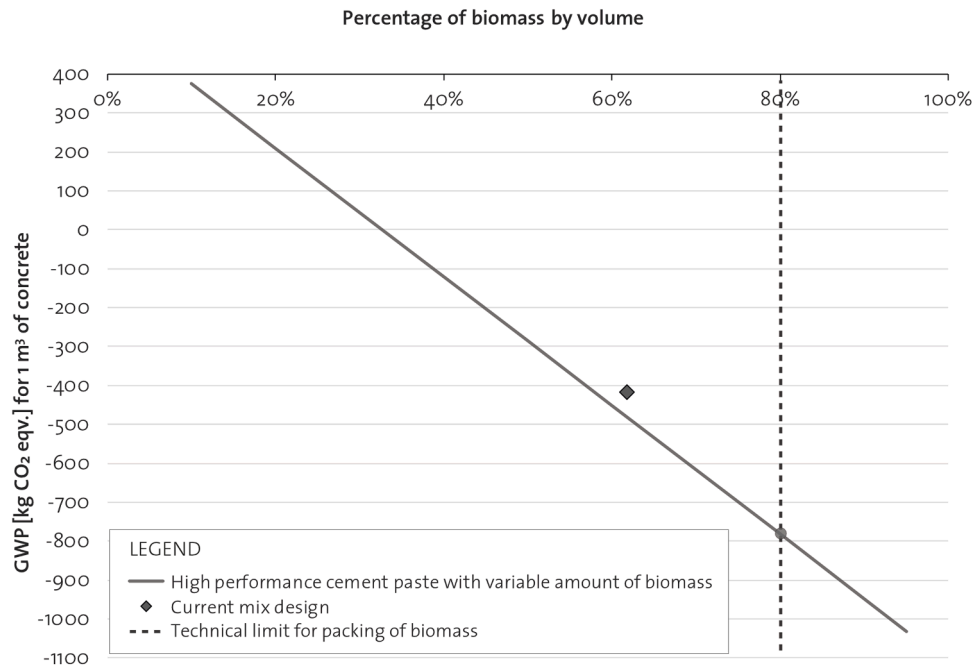


Fig. 3. Reverse engineering at the material scale: adjusting the amount of biomass and its effect on GWP of 1 m³ of ready-made BIC.

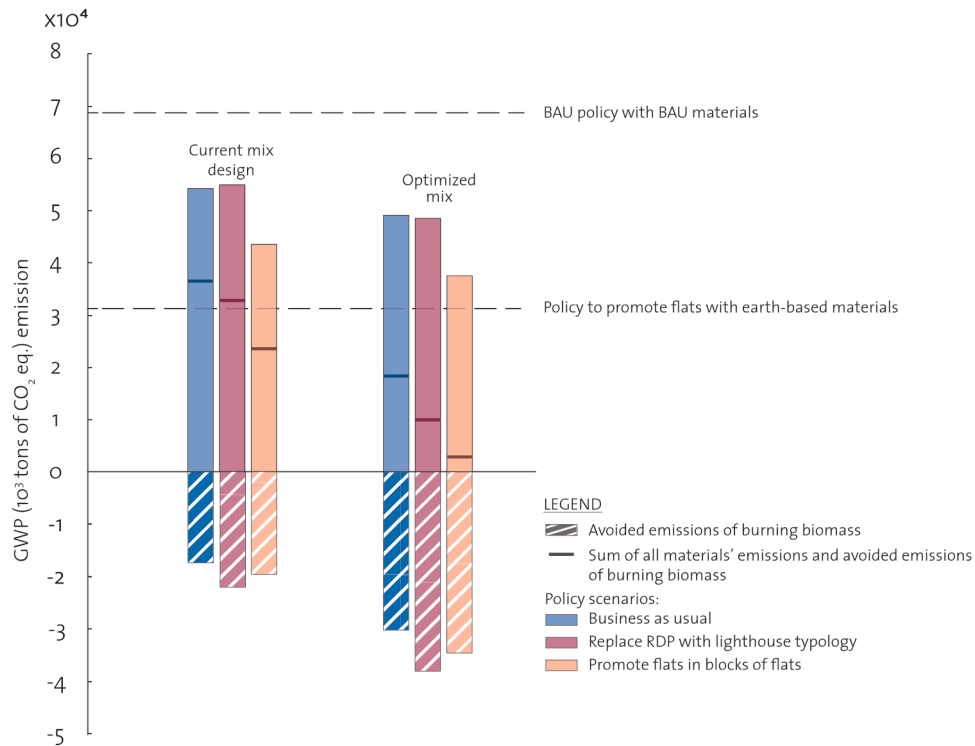


Fig. 4. Annual emission for all materials in 2050. The figure compares three different policy scenarios (in color) for the current BIC mix design and the optimized BIC mix (in grouped bars).

building stock. The lowest hypothetical value is achieved for the policy scenario to promote flats using the optimized Mix, which correspond to the results shown in Fig. 4. Even though not becoming completely carbon neutral, incorporating biomass in concrete has a significant potential towards reaching this goal. It needs to be noted that for this specific case, that is wanting to achieve carbon neutrality by accounting for avoided emissions of invasive wood-based concrete, it is more favorable to build houses that are material intense (here the flats and lighthouse

typology), than to aim towards lighter construction, e.g. the house on a separate stand, which account for the biggest share in the BAU policy scenario.

3.3. Additional benefits of using invasive woody based concrete

It is shown that a city-scale application of optimized BIC mix, in combination with a policy to promote flats, almost allows to achieve a

Table 2

Theoretical amount of biomass per 1 m³ of concrete needed to offset production impacts of concrete and other construction materials of the residential building stock for LC stages A1 and A3 from now until 2050.

Policy scenario	Current mix		Optimized mix	
	kg biomass per m ³ BIC	biomass% vol	kg biomass per m ³ BIC	biomass% vol
BAU	1'133	189%	744	124%
Lighthouse	914	152%	584	97%
Promote flats	800	133%	501	84%

carbon neutral building stock in Cape Town (refer to [Section 3.2.2](#)). Furthermore, there are additional benefits of using this material, namely clearing land of IAP and related to that the potential of saving water surface runoff. The amount of required land to source the invasive wood chips is estimated for the optimized BIC mix. In addition, an estimate of the saved water surface runoff related to IAPs reducing impact on streamflow is presented.

To estimate the reduced water surface runoff caused by IAPs for different tree species we employed the model parameters provided by [Le Maitre et al. \(2016\)](#). For tree density we assume the values for acacia and pine, the most common IAP species around Cape Town. [Mugido et al. \(2014\)](#) found that for acacia and pine 71.97 tons per hectare of condensed area can be harvested (the value of condensed invaded area is theoretical and obtained by the proportion or average density that is weighted). Data published by [Kotzé et al. \(2010\)](#) shows that for Cape Town the average density of IAP in the overall invaded land is 17.03%, while the city's surrounding quaternary catchments G and H (refer to [Le Maitre et al. \(2016\)](#)) have a lower average density as can be seen in [Table 3](#).

[Table 3](#) shows the parameters and also the results of the analysis for potentially cleared land and saved water surface runoff for the three different policy scenarios. The biggest potential has the policy scenario to substitute RDP with the *lighthouse* typology using the optimized BIC mix in the bio-based material scenario, which translates to 0.44 Mio hectare of condensed area that can be cleared from IAP. Depending on the spatially varying density of the IAP stands, the effectively cleared land can range between 2.61 and 6.99 Mio. hectare. These values are obtained through a translation of cleared condensed area to effectively cleared area based on the average density of IAP for Cape Town and surroundings, respectively. To put these values in context: the Cape Town Metropolitan Area is roughly 0.25 Mio hectare and the Western Cape Province 13 Mio. hectare. The last detailed data on existing IAP stands in South Africa was published in 2010 ([Kotzé et al., 2010](#)). However, considering a spread rate of 5% and a densification rate of 1% with no clearance (refer to [Preston et al. \(2018\)](#)), it can be estimated that currently in Cape Town 0.16 Mio hectare land are invaded by IAP. Across South Africa the estimate is at 160 Mio. hectare of invaded land.

Table 3

Overview of cumulative amount of cleared land and reduced water consumption until 2050 thanks to the urban-scale use of the optimized BIC mix for the residential building stock in Cape Town, based on the demand-driven model. The analysis is carried out for the characteristics of invaded land within the Cape Town Metropolitan area and compared to the results based on values of surrounding quaternary catchments. Coefficients are taken from [Le Maitre et al. \(2016\)](#), [Mugido et al. \(2014\)](#) and [Kotzé et al. \(2010\)](#).

Parameters for IAP stands in	Condensed area	Effective average density of IAP		Water reduction [m ³ /ha]	
Cape Town		17.03%		811	
Surroundings			6.35%		775
Hypothetical	100%				
		Land cleared [Mio. ha]		Water saved [Mio. m ³]	
Policy scenarios	Condensed area (at 100% density)	Effective area, with Cape Town values	Effective area, with surrounding values	With Cape Town values	With surrounding values
Business as usual	0.39	2.27	6.09	314	300
Substitute RDP with lighthouse	0.44	2.61	6.99	360	344
Promote flats	0.41	2.43	6.51	335	321

Moreover, the eradication of 0.44 Mio. condensed hectare corresponds to 344 - 360 Mio. m³ of saved water surface runoff. In comparison: in March 2018, as a reaction to the water crisis, the City of Cape Town restricted the water use to 0.5 Mio. m³ per day ([City of Cape Town, 2019](#)).

3.4. Uncertainties and future research

There are various uncertainties in the present study. They can be divided into uncertainties of (i) the building stock model, (ii) the natural systems model, and (iii) the considered LC stages, LCI and impact categories.

- Regarding (i), the service life distribution of buildings, and the construction rates, are uncertain but important drivers. For more information on these aspects, please refer to [Göswein et al. \(2018\)](#) that already analyzed low, medium, and high range scenarios for the different building stock drivers. Moreover, the study should be extended to analyze infrastructure since it contributes to 10–40% of a city's total built environment ([Augiseau, 2017](#));
- Regarding (ii), the inventory of IAP and the assumption of the fixed fire frequency (every 15 years) should be further analyzed. An analysis that highlights the importance of the transport-related impacts of IAP biomass can be found in SI III;
- Regarding (iii), more LCI data that is specific to South Africa should be collected. For the LCI of BIC the impacts related to the manufacturing of BIC, as well as the plant cutting and processing of IAP should be analyzed and included for refined studies of BIC. The here assumed incineration of materials at the building's EoL refers to the worst case scenario. However, [Pittau et al. \(2018\)](#) provide more information on other EoL scenarios of bio-based construction materials. Future research should also analyze additional impact categories, such as particulate matter including black carbon, and biodiversity loss related to the eradication of IAPs.

Conclusions

This study tested the urban scale application of a bio-based concrete using invasive alien wood chips regarding its potential to offset embodied GHG of construction materials by accounting for avoided emissions of burning biomass. An optimization at the material scale respecting mechanical properties of concrete increased the amount of avoided emissions and reduced the total amount of embodied GHG in the building stock until 2050. Combined with a policy that increases the share of buildings that are material intense in terms of BIC allows to drastically reduce the overall impacts of the building stock. An optimized mix that maximizes the maximum incorporation of biomass (80% Vol.) is proposed. Moreover, cement is replaced up to 60%, by fly ash. In combination with a policy to promote denser housing through the

promotion of blocks of flats, there is a real potential towards achieving carbon neutrality at the urban scale. However, the increased study boundary, i.e. urban scale, requires to include the transport-related impacts to source the IAP biomass for the production of BIC, which significantly increase the total impact of the bio-based material scenario.

Moreover, this specific example shows that it is worthwhile to aim towards technical solutions that are enabled through synergies, and to think of context-specific solutions. In this case, this was to provide adequate and low-carbon housing, while simultaneously providing additional benefits of using invasive wooden aggregates, namely eradicating a pest that destroys the natural ecosystems and exacerbates water shortages.

The methodology applied in this paper suggests possibilities of defining benchmarks and targets for bio-concrete in South Africa to define a mix design which, combined with the appropriate policies, can lead to a low carbon built environment. The suggested methodology links two approaches, demand-driven and reverse-engineering, to help forecast the building stock demand and to optimize the bio-based concrete. Comparing different material scenarios it was found that the bio-based scenario (substituting conventional concrete with BIC) is more advantageous with respect to the selected indicators, than using only traditional materials in a BAU scenario and also competitive, and in the right application even superior, to earth-based construction, the latter even though being an advantageous solution from an environmental point of view, can be considered too radical and encounters market entry barriers related to a lack of knowledge and understanding. Whereas enhancing a well-trusted material, concrete, has proven not only to be possible but likely also to be more successful at big scale implementation.

Supporting information

SI I – Impression of the lighthouse typology
 SI II – Summary of model input parameters
 SI IIIa – Local availability of IAP and the impact of transportation
 SI IIIb – Results of geo-spatial analysis for real transport distances as presented in SI IIIa
 SI IV – Map of invasive alien plants across South Africa
 SI V – GWP for all material and policy scenarios over time (per year and cumulative)

CRedit authorship contribution statement

Verena Göswein: Conceptualization, Methodology, Writing - original draft, Visualization. **José Dinis Silvestre:** Conceptualization, Writing - review & editing, Supervision. **Stephen Lamb:** Conceptualization, Resources. **Alexandre B. Gonçalves:** Visualization. **Francesco Pittau:** Conceptualization. **Fausto Freire:** Supervision. **Dirk Oosthuizen:** Resources. **Andrew Lord:** Resources. **Guillaume Habert:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2020.105361](https://doi.org/10.1016/j.resconrec.2020.105361).

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