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Demand-driven climate change mitigation and trade-offs from wood product substitution: The case of Swedish multi-family housing construction

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ABSTRACT

Multi-family housing construction (MFHC) with wood instead of concrete as frame material results in lower greenhouse gas emissions. Hence, substituting wood for concrete in MFHC in Sweden until 2030, and onwards to 2070, could be a promising climate change mitigation option. But to what extent, and how would it impact Sweden's forests? Here we assess climate and biodiversity implications - in terms of the area of old forest - of a completely wood-based future MFHC in Sweden. The wood required is assumed to be exclusively sourced as additional fellings in Swedish forests, thus carbon leakage from wood imports as well as displacement of other wood uses can be disregarded. Different types of timber frame systems and the role of varying future dwelling sizes are considered. We find that the wood needed for a complete substitution of concrete would result in very minor increases in harvests. We further register slight net additional climate change mitigation, irrespective of the wood construction system. There is a small tradeoff between climate change mitigation and biodiversity, as the area of old forest reduces slightly. The largest climate benefit, and lowest impact on Swedish forests, is provided when using timber-light frame combined with reduced dwelling size.

1. Introduction

Building materials and construction account for twenty percent of annual global carbon dioxide (CO_2) emissions (UNEP, 2022). The use of wood products in construction meanwhile appears to have one of the largest climate change mitigation potentials (Sathre and O'Connor, 2010; Leskinen et al., 2018; Myllyviita et al., 2021). Strong evidence thus indicates climate superiority of wood frame over concrete- and steel frame buildings (Gustavsson et al. 2017, 2021; Head et al., 2020; Andersen et al., 2022; Peñaloza et al., 2016; Chen et al., 2020; Cordier et al., 2021; Piccardo and Gustavsson, 2021; Himes and Busby, 2020; Mishra et al., 2022). Accordingly, the new EU forest strategy (EC, 2021a) maintains that the most important role of wood products is to help turn the construction sector from a source of greenhouse gas emissions into a carbon sink, as set out in the New European Bauhaus initiative (EC, 2021b). Indeed, there are numerous other national, and international initiatives and policy programs promoting the application of wood in construction for climate change mitigation and restoration, e. g., Built by Nature (Built by Nature, 2022), or Bauhaus Earth (Bauhaus Earth, 2022).

A relevant feature influencing the overall environmental burden of housing, regardless the material type, is the dwelling size per capita, e. g., in terms of energy consumption (Ivanova and Büchs, 2022). Throughout the past decades however, the average dwelling size per capita kept on increasing globally (Ellsworth-Krebs, 2020) although shrinking the dwelling area would lead to a generally decreased environmental impact. This highlights large potentials for downsizing or shared living in future design and construction of housing (Huebner and Shipworth, 2017; Ivanova and Büchs, 2022) irrespective of the materials applied.

Sweden is amongst the forerunners in the EU when it comes to wood-based construction (Trinomics et al., 2021). Timber frame (used synonymously with wood frame) dominates in the construction of

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List of Abbreviations

AGTP	Absolute global temperature change potential
ATF	Average timber frame
CLT	Cross-laminated timber
EU	European Union
EWP	Engineered wood product
DF	Displacement factor
HWP	Harvested wood product
GHG	Greenhouse gas
GLT	Glued-laminated timber
GWP	Global warming potential
LCI	Life cycle inventory
MFH	Multifamily-housing
MFHC	Multifamily-housing construction
RCP	Representative concentration pathway
SOC	Soil organic carbon
TLF	Timber light frame

single-family housing, with a market share of around 90% (Swedish Wood, 2023), while concrete still dominates as frame material in multi-family housing construction (MFHC), accounting for 80% during 2019–2020 (SCB, 2022a; SCB, 2022b). However, timber frame, with a share of 19% during 2019–2020 (Malmqvist et al., 2021; SCB, 2022a), has increased significantly in MFHC in absolute terms following changes in the building code in 1994, allowing timber frames in buildings with more than two storeys (Bengtson, 2003). Moreover, the use of timber frame in MFHC has been furthered by the introduction of engineered wood products (EWPs), such as cross-laminated timber (CLT) and glued-laminated timber (GLT). Hence, EWPs have enabled the construction of functionally equivalent wood-based buildings in terms of safety and technical requirements (Gustavsson et al., 2021; Andersen et al., 2022). In addition, consumers positively associate timber frame housing with environmental and social sustainability aspects which enables for increased opportunities to capture market advantages (Roos et al., 2022).

To meet expected demographic trends, 600,000 new dwellings need to be built until 2030 in Sweden (Boverket, 2021; SCB, 2022a), chiefly in multi-family housing (MFH) given its dominance in residential construction, making up 77% of recently built dwellings (SCB, 2022a). Thus, there is a considerable potential for timber frame to substitute for concrete frame in MFHC. Accordingly, we intend to explore implications in terms of climate change mitigation potentials and the future state of Swedish forests of a complete substitution of concrete by timber in MFHC from 2030 and onwards in Sweden. Sourcing the wood needed exclusively through increased domestic fellings implies that other uses of wood are not displaced.

In terms of a system perspective of the forest sector (EC, 2021a), a common – in Sweden hitherto dominant – approach when assessing climate change mitigation potentials of forest management and the associated wood use is that of a supply-perspective, “from-the-forest-to-the-wood-use”. Substitution effects are estimated for the harvested wood products (HWPs) that result from annual harvest volumes, often by using substitution, or displacement factors (DFs) on product (Sathre and O’Connor, 2010), or market level (Hurmekoski et al., 2021).

Hence, the supply-perspective credits HWPs with avoidance of greenhouse gas (GHG) emissions, i.e. substitution effects, merely due to their supply and without accounting for the demand. The overriding premise is that an increase in production of the wood-based commodity in question results in an equal increase in total consumption thereof, which amounts to an (implicit) assumption of perfectly elastic demand (Mas-Colell et al., 1995). Indeed, a major shortcoming of many studies is that critical assumptions applied, such as the issue of market effects leakage (Aukland et al., 2003) are rarely explicitly stated and addressed (Schweinle et al., 2018; Harmon, 2019; Jonsson et al., 2021; Hurmekoski et al., 2022). As a result, wood product substitution effects are often overestimated (Leturcq, 2020). This as substitution is only effective as far as (i) an increase in the supply of a wood product in a certain region results in an equal increase in the Global consumption of this wood product (i.e., there is no market effects leakage), in turn leading to (ii) a Globally verifiable reduction in non-wood products. Otherwise the manufacture of the wood product merely adds to overall supply (Hurmekoski et al., 2022) and thus results in net additions of GHG emissions.

In order to address this inconsistency, a demand-perspective for modelling climate change mitigation potentials of wood use can be applied. In contrast to the former, this perspective follows “from-the-wood-use-to-the-forest” and is targeted to a specific HWP application, e.g., construction. Adopting the United Nations Framework Convention on Climate Change’s (UNFCCC) view on mitigation (UNFCCC, 2022), the substitution effect here is stated as a relative concept, i.e., absolute avoided emissions in alternative scenarios that deviate from a reference or baseline scenario, leaving the estimation of a DF an optional feature (Hurmekoski et al., 2021). The alternative scenarios and the reference are characterized by differing amounts of HWPs and substituted alternatives. GHG balances on the product level rely on life cycle inventory (LCI) data. This assessment approach was, e.g., applied by Hafner and Rüter (2018) to investigate the climate benefit of increased residential wood-based buildings in Germany based on national projections.

We apply a demand-perspective in analyzing the climate change mitigation potential at national level of an increased use of wood-based MFHC in Sweden. This is done by integrating LCI data at the building level, Swedish residential housing statistics, projected housing demand, and demographic projections. This approach avoids the assumption of a perfectly elastic demand in wood-based markets and circumvents estimating the share of different end-uses in the consumption of semi-finished wood products in question, as necessary when applying the supply-perspective.

As such, the study assesses climate and biodiversity implications of an entirely wood-based future Swedish MFHC, when the wood required is sourced from Swedish forests, and thereby not induces imports or displaces other wood uses. Climate impacts are estimated within the short (<20 years) to medium term (<50 years). Biodiversity impacts of ensuing increased harvests of roundwood are assessed using the indicator of old forest area, (Sveriges Miljömål, 2023; Swedish University of Agricultural, 2023). We ascertain which type of wood-based construction system and associated wood-use intensity would result in the largest climate benefit and consider the role of future dwelling sizes in MFHC for climate change mitigation. The outcomes are, in addition to GHG emissions, assessed in terms of time dynamic temperature change as to when and to which extent potential climate change mitigation occurs.

2. Materials & methods

2.1. System boundaries

Fig. 1 shows the system boundary of the study which is geographically limited to Sweden. The modelling starts with the projected demand for MFHC in Sweden and scenarios (Section 2.2). This demand can be met by two dwelling alternatives: a concrete frame, or a wood frame dwelling each of which requires certain types and amounts of materials. Thus, two representative dwelling equivalents are defined and their construction is upscaled to the national level (Section 2.3). In order to account for the climate effects due to changes in the relative share of the dwelling equivalents, a technosystem as well as a forest system are defined where the supply of all materials used for the dwelling alternatives are backtracked from the wood end-use application to the origin (“cradle”) (Section 2.4). Within the technosystem some parts are “cut-off” the system boundary, notably downstream use of some sawmill by-products, upstream logging residues and pulpwood use. A crucial ceteris

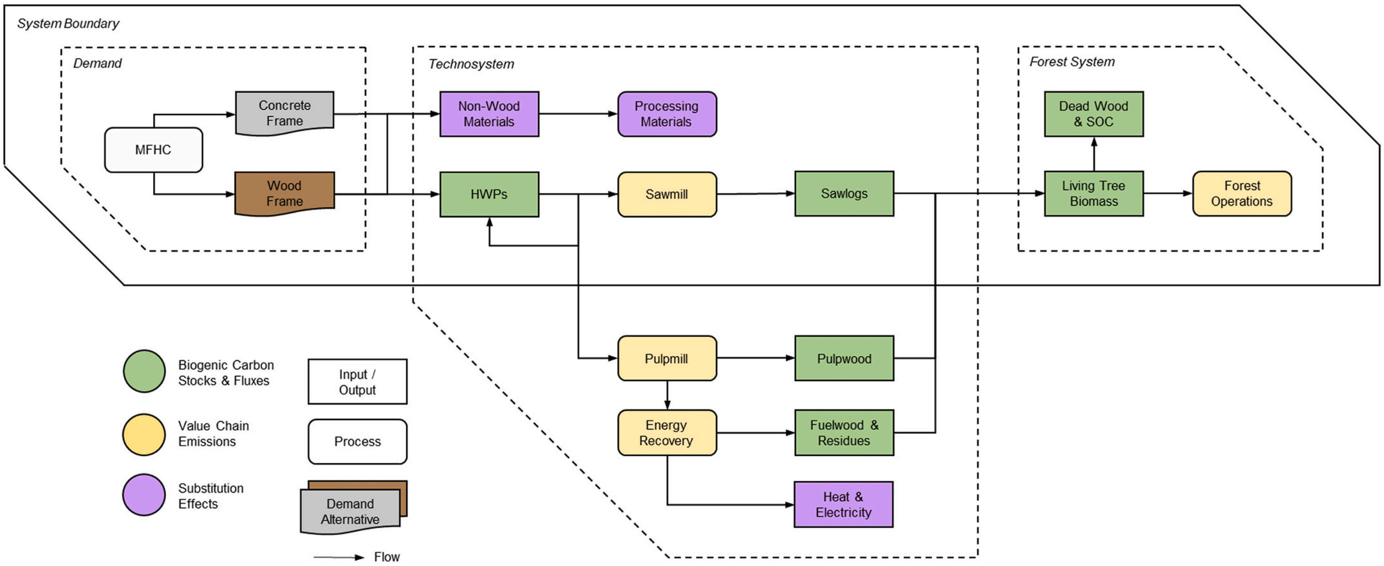

Fig. 1. System boundary starting from the demand of additional multi-family housing construction (MFHC) met either by concrete frame or wood frame, and continuing over implications within the technosystem, and the forest system. Note that parts of the technosystem are "cut-off" from the system boundary, and that only MFHC-related by-product-based HWPs from sawmill activity are included (particleboard), but other HWPs made from sawmilling by-products (e.g., furniture use) are excluded. HWP: harvested wood product.

paribus assumption is thus that the wood used for additional increases in wood-based construction is entirely sourced from additional fellings in productive Swedish forests only, while not impacting other wood uses and associated non-wood product value chains. We focus here on the required additional dwellings and increasing wood share in MFHC only. This, as single-family houses only account for the minority of recently built dwelling types (23%), and wood frame here is already dominating the market as load-bearing structure with a share of around 90% (Swedish Wood, 2023). Given the multitude of different dwelling sizes and forms in MFHC, the functional unit during the calculations was adapted to a square meter (m^2) of living area.

2.2. *Multifamily-housing demand, future reference projection and scenarios*

Fig. 2 presents annual historical MFHC by type of frame material for Sweden from 1995 until 2020, and a reference projection as well as two scenarios all ranging from 2021 until 2030 and reaching 2070, based on (SCB, 2022a, 2022b; Boverket, 2021). In the past, from 1995 until 2020, concrete frame was the dominating construction type, on average with an 87% share while wood frame gained an increasing application share over time, accounting, on average, for about 13% throughout 1995–2020, and increasing to around 19% during 2019–2020.

In the future, we assumed that both, the reference projection, and the scenarios meet the expected housing demand of 461,000 additional dwelling units in MFH by 2030, according to the average MFHC market share of 77% from the past five years. In total that is a MFHC increment of 3.1% per annum until 2030. Past 2030 until 2070, both, reference projection and scenarios are assumed including an average MFHC increment of 0.4% in accordance with projected demographic developments in Sweden (SCB, 2022c).

In the reference projection the relative share among concrete frame and wood frame in a growing MFHC market until 2070 is set conservatively and maintains today's proportion of 81% concrete frame and 19% wood frame. In contrast, the two scenarios increase the wood frame share by 18.1% per annum as compared to the reference projection from 19% in 2020 to 100% in 2030 and keep it stable on this level until 2070. The first scenario, "Average Timber frame", in the following referred to with "ATF" scenario, maintains the Swedish market shares of the three current wood frame types and thus equals a weighted average of timber

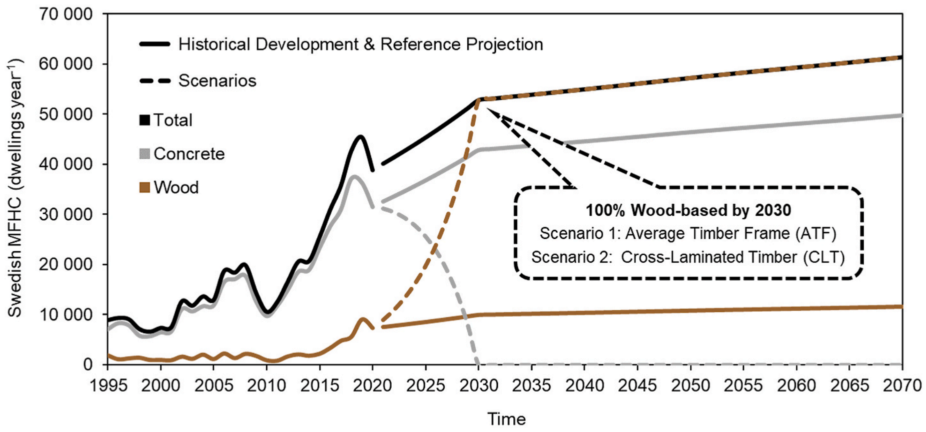

Fig. 2. Annual historical Swedish MFHC (1995–2020) (SCB, 2022a, 2022b), reference projection, and scenarios (2021–2070), given per frame material used. MFHC = Multi-family housing construction.

light-frame constituting 85% (Rudenstam 2021), and, in absence of information, assumptive 7.5% market shares of cross-laminated timber and glued-laminated timber, respectively. The second scenario, "Cross-Laminated Timber", in the following referred to as "CLT" scenario, accounts for gradual decreases in the timber light-frame and glued-laminated timber shares. The scenario assumes that by 2030, 100% of additional wood-based dwellings are made out of cross-laminated timber which then keeps constant until 2070. Table 1 summarizes the reference projection and scenario assumptions. To varying degrees, both scenarios thus entail an additional demand of HWPs and thus outtake of roundwood from Swedish forests, which is benchmarked against the counterfactual reference projection that foresees a continuation of underlying trends in the demand and provision of wood products. Note that the residual frame types apart from concrete frame and wood frame, such as steel, were excluded from the analysis due to negligible market shares.

2.3. *Dwelling equivalents and upscaling procedure to the national level*

To reasonably determine and compare wood frame and concrete frame MFHC alternatives, and their future projections in terms of their climate performance, functionally equivalent dwelling archetypes are required. However, types and amounts of resources applied in both dwelling alternatives can differ substantially, which necessitates an approximation thereof as presented in Table 2 per m^2 in the functionally equivalent wood frame and concrete frame dwelling archetypes. For this, the material inventory from Gustavsson et al. (2017) was used as the basis for modelling, as it enables to represent an average wood frame dwelling that allows accounting for timber light frame, cross-laminated timber, and glued-laminated timber market shares. These three wood frame types, and the concrete frame alternative, are functionally equivalent building archetypes characterized by the same energy use and building service covering a lifetime of 80 years. In this instance, the carbonation process of the concrete applied was disregarded as it is considered not to generally alter climate results from comparisons of wood frame and concrete frame buildings, see, e.g., Dodoo et al. (2009). The amount of total air-dry wood use per living area in the weighted average timber frame dwelling is 89 kg m^{-2} (ATF scenario) and in the cross-laminated timber dwelling 109 kg m^{-2} (CLT scenario). In the concrete frame alternative it amounts to 66 kg m^{-2}. See the Supplementary Material for more detailed information.

The production related fossil GHG emissions of all wood frame and the concrete frame dwelling equivalents were deduced using LCI data from the Ecoinvent 3.8 database (Wernet et al., 2016). Here, the emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were inventoried for all resources applied, except for rubber and crushed stones, whose emissions are negligible (Supplementary Material). Table 3 summarizes these fossil value chain emissions in form of the global warming potential (GWP_{100}) in the unit of Mg CO_2 equivalents (Mg CO_2 eq). A square meter living area of the concrete frame dwelling amounts to 0.25 Mg CO_2 eq, while both, the weighted average timber frame alternative (ATF scenario) and the cross-laminated timber dwelling (CLT scenario) constitute 0.11 Mg CO_2 eq. Upscaled to the dwelling level, this amounts to 14.2 Mg CO_2 eq of fossil value chain emissions for the concrete frame, 6.3 Mg CO_2 eq per weighted average timber frame alternative (ATF scenario), and 6.1 Mg CO_2 eq per cross-laminated timber dwelling, considering an average Swedish dwelling size of 57 m^2 (SCB, 2016).

Table 1
Swedish MFHC reference projection and scenario properties from 2021 to 2030, and 2031 to 2070. MFHC = Multi-family housing construction; TLF = timber light frame; CLT = cross-laminated timber; GLT = glued-laminated timber. See the Supplementary Material for more detailed information.

Property	Reference Projection	Scenario 1: ATF	Scenario 2: CLT
Annual MFHC increment during 2021–2030 and 2031–2070, respectively	3.1% 0.4%	3.1% 0.4%	3.1% 0.4%
Annual wood frame MFHC increment during 2021–2030 and 2031–2070, respectively	0% 0%	18.1% 0%	18.1% 0%
Relative distribution of wood frame MFHC after 2030	85% TLF 7.5% CLT 7.5% GLT	85% TLF 7.5% CLT 7.5% GLT	0% TLF 100% CLT 0% GLT

Table 2
Type and amounts of required materials of the concrete frame, average timber frame and cross-laminated timber dwelling equivalent given in kg m^{-2} living area, based on Gustavsson et al. (2017). The average timber frame dwelling comprises 85% timber light frame, 7.5% glued-laminated timber frame, and 7.5% cross-laminated timber frame, respectively.

Material	Concrete Frame Dwelling	Average Timber Frame Dwelling	Cross-Laminated Timber Frame Dwelling
Concrete	1138.6	100.6	96.6
Steel	21.4	3.6	4.4
Aluminum	0.0	0.5	0.5
Mortar	19.6	9.8	14.9
Stone-Wool Insulation	11.1	2.1	13.6
Glass-Wool Insulation	1.3	10.9	0.0
Plasterboard	21.2	85.7	60.8
Polyvinylchloride	1.6	0.6	0.6
Polyurethane	0.0	4.2	3.4
Expanded Polystyrene	2.4	2.4	2.4
Crushed Stone	267.0	265.0	265.0
Lumber (Sawnwood)	34.7	43.5	36.3
Cross-Laminated Timber (CLT)	0.0	7.2	46.0
Laminated Veneer Lumber (LVL)	0.0	3.8	0.0
Glued-Laminated Timber (GLT)	0.0	8.7	17.0
Particleboard	14.6	15.1	3.3
Plywood	16.7	6.9	5.6
Laminated Wood Flooring	0.0	3.8	0.5
Wood Use	66.1	89.1	108.7

Table 3
Fossil GHG profiles of concrete frame, average timber frame (ATF scenario) and cross-laminated timber frame (CLT scenario), given per dwelling unit (average size of 57 m^2) and m^2 living area, expressed in Mg CO_2 eq.

Level	Unit	Concrete Frame	Average Timber Frame	Cross-Laminated Timber Frame
Dwelling Unit	Mg CO_2 eq	14.17	6.28	6.11
Square meter living area	Mg CO_2 eq	0.25	0.11	0.11

The subsequent upscaling from the dwelling to the national level was done by linking the fossil GHG emission profiles at the dwelling level with the reference projection and scenarios as defined in Section 2.2. The relative demand differences of wood-based construction between the reference projection and the scenarios thus induced relative changes in fossil GHG emissions (substitution effects), and in biogenic carbon balances in HWPs and the originating Swedish forest. Consequently, the definition of a reference wood product technosystem and forest system is required.

2.4. *Techno- and forest system*

2.4.1. *Technosystem*

Within the technosystem, additional HWP carbon storage and the fossil GHG emissions per additionally built dwelling equivalents as defined in Section 2.3 were accounted for. To receive the relative change of the HWP carbon storage pool, the conversion from the additionally demanded HWP amount per dwelling was performed to the amount of roundwood increments of sawlogs.

Retracing the increased sawlog processing in sawmills was identified by backtracking the additional net HWP amount given in kg HWP m^{-2} of dwelling area to the originating additional sawlog harvest in m^3 (under bark) which was required to meet the additional demand. For this, each HWP amount given in kg HWP m^{-2} was first converted into its volume, i.e., m^3 HWP m^{-2}, using conversion factors for Swedish conditions (FAO, 2020). In a second step the volume of each HWP per square meter, i.e., m^3 HWP m^{-2}, was converted into the volume of roundwood equivalents, i.e., m^3 roundwood under bark m^{-2} (Mantau, 2010), corresponding to each HWP in use, including cross-laminated timber and glued-laminated timber (Werner, 2022a, 2022b). Accordingly, the weighted average timber frame dwelling (ATF scenario) uses 0.19 m^3 m^{-2}, and the cross-laminated timber equivalent (CLT scenario) uses 0.24 m^3 m^{-2}. However, considering the density of the different HWPs applied and the conversion rate from carbon to CO_2 of 3.67, the retained biogenic carbon amount in HWPs amounted to 879 kg CO_2 eq m^{-3} for the weighted average timber frame dwelling (ATF scenario), and to 843 kg CO_2 eq m^{-3} for the cross-laminated timber dwelling (CLT scenario). See the Supplementary Material for details.

The increased demand of wood-based construction in the scenarios steered the additional sawlog processing and roundwood harvest volume. The net additional sawlog processing and roundwood harvest volume equals the difference between the saved sawlogs from the substituted concrete frame dwellings, and the increased requirement for sawlogs for the wood frame dwellings. As this could potentially impact other uses of wood, notably those using side-streams originating from sawmill activity, and their preceding inputs (pulpwood, fuelwood, and residues), as well as succeeding outputs (substitution effects from pulpwood products and energy recovery), these were "cut-off" from the system boundaries for simplification reasons, as stated under Section 2.1. Further we assumed that particleboard manufacturing in the scenarios was entirely based on sawmilling by-products (sawmilling by-products and pulp logs are perfect substitutes in this context), which is reasonable given the abundance of sawmilling by-products. The leftover amount not used for particleboard production, i.e., the "surplus" of by-products were "cut-off" the system boundaries. See the Supplementary Material for more information.

For the HWP carbon storage accounting, half-life times of 35, and 25 years were applied for sawnwood-based (lumber, CLT, glulam), and panel- or board-based (laminated veneer lumber, particleboard, plywood, laminated wood flooring) products, respectively (Rüter et al., 2019).

2.4.2. *Forest system*

In accordance with the demand-perspective stated above "from the end-use to the forest", the net annual roundwood harvest volumes of sawlogs were used as input in the forest decision support system Heureka PlanWise (Wikström et al., 2011) to simulate the relative implications on the forest carbon pool. In parallel, Heureka PlanWise served as the modelling tool to define the reference forest system, comprising biogenic carbon stocks from living tree biomass, soil organic carbon (SOC), and dead wood, as well as the reference national harvest levels. For the latter, the business-as-usual scenario of SKA 22 (the official Swedish forest impact analysis) was applied (Eriksson et al., 2022).

The forest system was geographically set to the productive forest land in Sweden and based on the National Forest Inventory (NFI) data from 2020. The productive forest land ($\geq$1 m^3 growth ha^{-1} $year^{-1}$) amounts to around 24,000,000 ha and excludes non-productive forestland (<1 m^3 growth ha^{-1} $year^{-1}$) equalling around 4,300,000 ha. On productive forest land, voluntarily and formally set-aside areas were excluded for the analysis. The mean wood volume on productive forest land equals 139 m^3 ha^{-1}, excluding the nature reserves and set-aside lands, and the average annual harvest volume during the past five years (2017–2021) amounted to 93,240,000 m^3 ha^{-1} $year^{-1}$ (Skogsstyrelsen, 2022a). The mean age at final felling throughout the past five-year average equals 100 years (Skogsstyrelsen, 2022b). Computation of biogenic carbon in living trees was done using biomass expansion factors. For above-stump tree biomass these were based on Marklund (1988) and for stump and root biomass on models by Petersson and Ståhl (2006). Within young stands, above-ground tree biomass was estimated by models by Claesson et al. (2001) and decay of coarse woody debris based on Kruys et al. (2002) and Sandström et al. (2007). SOC calculation on mineral soils relied on the Q-model (Ågren and Hyvönen, 2003) that computes continuous soil organic matter decomposition, and emission factors for peatland. Deadwood carbon was assessed with exponential decay rates from dead wood inflow following tree mortality (Harmon et al., 2000). During the simulations neither detrimental nor beneficial influences of climate change were included as the available tools in Heureka do only implement positive effects, i.e., increased biomass growth, but do not enable to anticipate negative effects, i.e., increased occurrence of calamities.

The reference levels for national harvest for sawlogs and pulpwood were based on GLOBIOM simulations under the absence of any representative concentration pathway (RCP) climate change model (Havlík et al., 2018; Lauri et al., 2021). These reference harvest levels worked as the absolute benchmark to which the additional roundwood harvest volumes of sawlogs from the scenarios were added. This increased harvest intensity amounted to the overall relative forest carbon difference and thus constituted the climate impact occurring within the forest system.

2.5. *Climate impact metrics*

The climate effect assessment via the global warming potential metric, GWP_{100}, was complemented with the absolute global temperature change potential (AGTP) as an additional climate metric along the cause-effect chain from emissions to climate change (Fuglestvedt et al., 2003, Myhre, 2013). In contrast to GWP_{100}, the AGTP accounts for timing of emissions and associated atmospheric dynamics. It is expressed in degrees of kelvin (K) and equals the response in global mean surface temperature at a certain point in time due to a shift in radiative forcing from a GHG pulse emission, i.e. CO_2, CH_4, or N_2O. Thus, AGTP considers timing of GHG emissions and their perturbation lifetimes which enables assessments of time dependent dynamics of (time dynamic) climate effects. Perturbation lifetimes of CH_4, and N_2O were 12.4 and 121 years, respectively, and the one from CO_2 was based on the Bern carbon cycle model (Joos et al., 2001, 2013), where the molecule remains airborne until it is taken up by oceans or the biosphere. The AGTP is described by:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H-t)dt \tag{1}$$

where radiative forcing (RF), expressed in W m^{-2}, and the climate response function (R_T) constitute a convolution over the assessed time horizon (H) induced from a change in RF due to a pulse emission of a GHG *x*. The term AGTP is used in the following synonymously with the term temperature change.

3. Results & discussion

3.1. *Additional roundwood demand and impact on Swedish forests*

Fig. 3 shows the cumulative additional roundwood volume demand in form of sawlogs for both scenarios under bark. Overall, the full concrete frame phase-out until 2030 induces an increasing sawlog harvest until 2030 and beyond until 2070. Starting in 2021, the ATF scenario provokes a cumulative additional roundwood demand of 1.1 million (M)

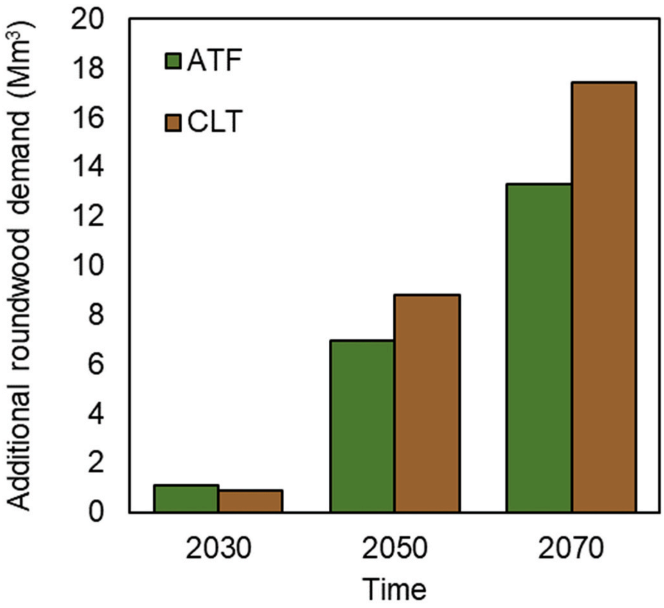

Fig. 3. Cumulative additional sawlog harvest volumes induced by the wood frame scenarios ATF and CLT respectively, given in million m^3 roundwood equivalents (under bark) as compared to the reference projection. ATF = average timber frame, CLT = cross-laminated timber. See Fig. 2 for more information on scenarios.

m^3 by 2030 and 13.3 Mm^3 by 2070. In contrast, the CLT scenario induces a slightly smaller cumulative harvest demand until 2030 with 0.9 Mm^3 due to the relative shift from timber-light frame dominance to cross-laminated timber. However, from 2030 until 2070 the CLT scenario requires about 1.4-times more compared to the ATF scenario which accumulates to 17.4 Mm^3. In terms of annual averages until 2050 this represents 0.1 Mm^3 $year^{-1}$ for the ATF scenario, and 0.3 Mm^3 $year^{-1}$ for the CLT scenario, which compared to the annual Swedish sawlog harvest volume during 2016–2020 would amount to only 0.7% and 1.6%, respectively (SFA, 2022). We thus find that the additional wood required for completely substituting concrete as a framing material in Swedish MFHC could easily be sourced entirely from national forests, even considering the more wood-intensive cross-laminated timber frame alternative.

In terms of the projected Swedish annual sawlog demand from 2020 until 2050 of 38.6 Mm^3 $year^{-1}$ (Lauri et al., 2021), the additional sawlog demand given in the scenarios would constitute a range from only 0.3%–0.4%. Carbon leakages within the wood-based sector would thus be virtually inexistent under the assumptions of the scenarios. This could guarantee real emission reduction within the Swedish forest sector, which without a self-sufficient national wood supply would require, e.g., a global carbon trading market to counteract carbon leakage (Pan et al., 2020). The additional average harvest area, including thinnings and final fellings, would extend from 0.7% (166,000 ha $year^{-1}$) under the ATF scenario to about 1.6% (383,000 ha $year^{-1}$) under the CLT scenario compared to present national productive forest land in Sweden, considering the entire time-frame from 2021 to 2070 and the current average sawlog harvest volume of 1.6 m^3 ha^{-1} (SFA, 2022). This is in accordance with the findings of Andersen et al. (2022), who, on a global level, note that only 3% of the forest area would be required by 2060 to meet future construction projections. The present study thereby can be seen as supporting the observation that global forest resources are more than sufficient for a future dominance of wood-based construction (Churkina et al., 2020), in addition to maintaining supply for other wood uses.

Increased wood harvest from Swedish forests could, however, compromise other ecosystem services, foremost biodiversity-related ones (Mazziotta et al., 2022; Chaudhary et al., 2016). These are typically found to be highest within old forest stands, i.e., 120–185 years old (Jonsson et al., 2020). Fig. 4 shows how the increased wood harvest following the scenarios provokes a decline in old forest areas in Sweden. This decline reduces the average old forest area of 1,150,000 ha $year^{-1}$ which is simulated from 2021 until 2070 under the reference projection. The ATF scenario causes an additional decline of −5300 ha $year^{-1}$ and the CLT scenario nearly the threefold with −14,500 ha $year^{-1}$. The additional decrease in old forest would thus range from −0.5% to −1.3% in comparison to the projected reference. In parts of the boreal forests of Sweden, where the limit for what is considered as old-growth forests is 140 years of age, this could, in addition to a decline in biodiversity-related ecosystem services, result in a non–optimal rotation age for carbon sequestration, which is estimated at 138 years (Peichl et al., 2022). In summary this supports the findings of Andersen et al. (2022) that wood-, in particular cross-laminated timber-based, construction may not hold a superior environmental performance in all environmental impact categories compared to concrete alternatives. Moreover, it highlights the apparently increasing ecosystem service trade-off that more bioeconomy-intensive forest management strategies may incur if aimed at maximizing wood harvest (Mazziotta et al., 2022).

3.2. *Climate impact of a complete wood-based multi-family housing construction*

3.2.1. *GHG balance including substitution effects and biogenic carbon*

The GHG balances of both scenarios including changes in fossil emissions, and biogenic carbon from HWPs as well as the forest system, are presented in Fig. 5 in a relative sense, i.e., as the difference to the reference projection. Both scenarios induce a negative net effect in the GHG balance, i.e., they provide a net climate benefit, when benchmarked to the concrete frame dominance in MFHC found in the reference projection. The dominating contributor in both scenarios is the substitution effect from the avoided fossil GHG emissions of the concrete

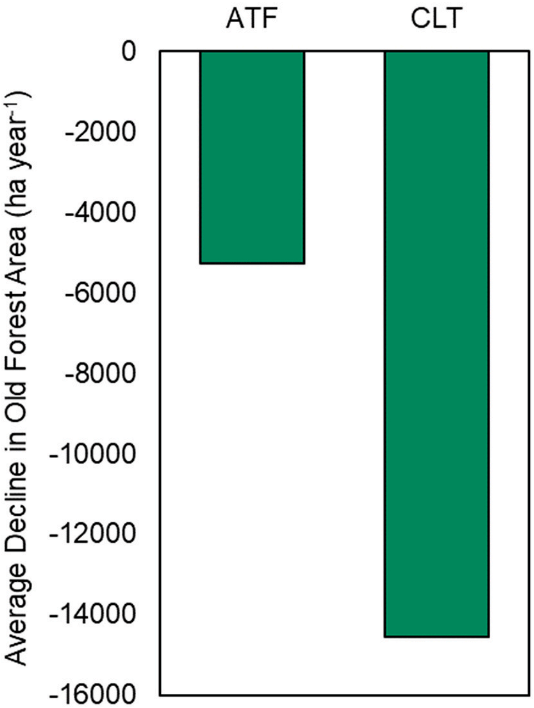

Fig. 4. Average annual decline in old forest area induced by the wood frame scenarios ATF and CLT respectively, given in ha $year^{-1}$, as compared to the reference projection. ATF = average timber frame, CLT = cross-laminated timber. See Fig. 2 for more information on scenarios.

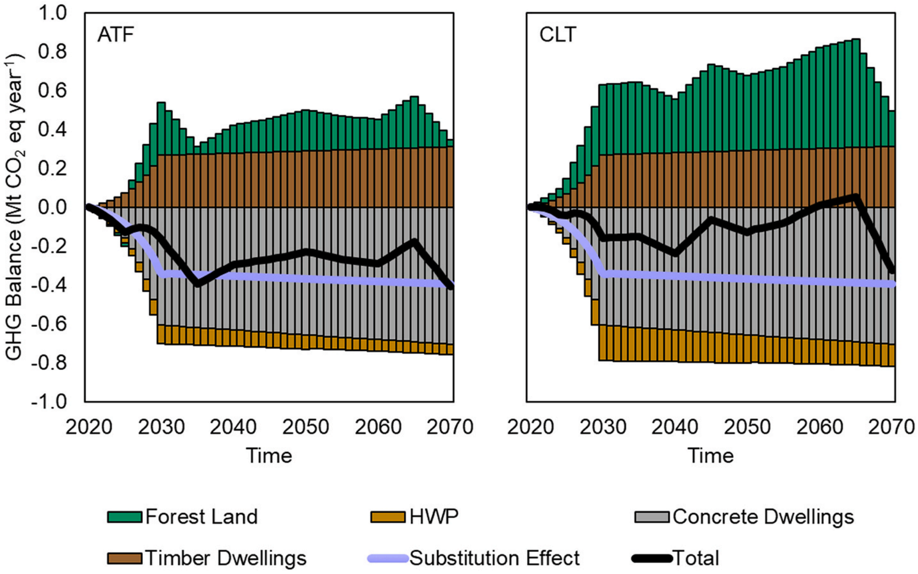

Fig. 5. Annual GHG fluxes of the ATF and CLT scenario as compared to the reference projection, i.e., the relative change in the GHG balance from a system perspective. Note that positive values correspond to emissions and that the substitution effect presented here corresponds only to the difference in fossil GHG balances. GHG = greenhouse gas, HWP = harvested wood product, ATF = average timber frame scenario, CLT = cross-laminated timber scenario. See Fig. 2 for details on scenarios.

dwellings for which the projected MFHC demand sets a cap for the achievable maximum (demand-perspective). By that, methodological shortcomings and a lack of data associated with a supply-perspective that necessitates assumptions of perfect substitutes (Hurmekoski et al., 2022) and shares of different end uses of wood products - e.g., the shares of different end uses of softwood sawnwood in Sweden - were circumvented. However, substitution effects which here are assumed constant may change over time. They may decrease under future decarbonization efforts of, e.g., the energy sector, or the concrete manufacturing industry, or due to increased recycling efforts in non-wood industries, as shown for Nordic wood-based construction in Myllyviita et al. (2022). In contrast they may however also increase due to, e.g., improved efficiencies in the wood manufacturing industry. As a consequence, biogenic carbon balances from the forest and the HWPs applied in construction may receive a larger or smaller relative importance in climate change mitigation. Biogenic carbon effects found here however are of minor magnitude in comparison to the substitution effect. The increased HWP carbon storage contributes moderately to the climate benefit whereas the forest system accounts for larger biogenic carbon losses due to increased harvests which fluctuate across the time-horizon due to regional forest age-class dynamics.

Overall, the ATF scenario leads to potential cumulative net GHG savings of around −1.0 Mt CO_2 eq by 2030, -6.8 Mt CO_2 eq by 2050, and -12.1 Mt CO_2 eq by 2070. This substantially outperforms the GHG savings from the CLT scenario, which cumulatively avoids a potential of −0.5 Mt CO_2 eq by 2030, -3.4 Mt CO_2 eq by 2050, and -4.7 Mt CO_2 eq by 2070. In comparison to the total GHG emissions in Sweden during the year 2021 of around 48 Mt CO_2 eq (SCB, 2023), the annual average emission mitigation from the ATF or CLT scenario would thus comprise 0.5% (−0.24 Mt CO_2 eq year^{-1}) or 0.2% (−0.09 Mt CO_2 eq year^{-1}), respectively.

This net climate benefit of both scenarios representing the wood-based replacement of concrete frame in Swedish MFHC thus corroborates earlier findings of a superior climate-performance of wood-based construction over concrete-based (Gustavsson et al. 2017, 2021; Piccardo and Gustavsson, 2021; Andersen et al., 2022; Churkina et al., 2020; Hildebrandt et al., 2017; Myllyviita et al., 2022). This outcome could be further substantiated if potential substitution effects of the "surplus" by-products being "cut-off" from the system boundaries were also considered. This is, however, simply not feasible since that would require information as to (i) the demand of all the end-uses that the "surplus" by-products could be used to manufacture, and (ii) their respective input mixes. If (i) and (ii) were at hand, then, still (iii) a considerable fraction of the "surplus" by-products would not lead to a substitution effect, since a considerable share would be used, e.g., for increased internal energy generation in sawmills, or for graphic or hygiene paper production. The exact amount used for these applications we are not able to estimate though.

Moreover, the results support earlier findings that increased biomass removal from forests induces a decrease of carbon accumulated in forest soils and trees (Seppälä et al., 2019; Soimakallio et al., 2021; Mazziotta et al., 2022) which can only partly be compensated for by the increase in the carbon pool of harvested wood products (Soimakallio et al., 2022). From a climate, as well as from a biodiversity perspective, this emphasizes the importance to aim for the most efficient wood utilization possible.

3.2.2. *Implications of different wood-based construction alternatives*

The increased climate benefit from timber light frame that dominates Swedish wood-based construction today (ATF scenario), compared to cross-laminated timber and glued-laminated timber, mainly originates from a lower wood use ratio per dwelling unit, which confirms the findings from Gustavsson et al. (2017) and Ruuska and Häkkinen (2012) (Myllyviita et al., 2022). However, this ratio can change substantially, for example given other material inventory data per building. More recent material inventories within a Swedish setting exist for both wood frame and concrete frame MFHC (Peñaloza et al., 2019; Piccardo and Gustavsson, 2021). However, for the purpose of this study, either an insufficient material breakdown for the concrete frame alternative was given (Peñaloza et al., 2019) or a specific market share breakdown into timber light frame, cross-laminated timber, and glued-laminated timber was infeasible (Piccardo and Gustavsson, 2021). Furthermore, different functional units among the studies impede a valid comparison between the wood frame and concrete frame dwellings.

In contrast to its less efficient wood use however do cross-laminated timber and glued-laminated timber allow for larger construction application ranges in comparison to timber light frame, e.g., due to improved dimensional stability and mechanical performance (Hurmekoski et al., 2015). This enables the applicability for high-rise building construction extending over conventional mid-rise MFH options. Especially in terms of sustainable planning of urban residential areas with more efficient use of space which aims for minimizing further land use change by land sealing, this may pose additional benefits over a conventional timber light frame application. This benefit is complemented by the potential that future cross-laminated timber may be produced using smaller wood assortments which would pose another advantage over timber light frame. Moreover, cross-laminated timber and glued-laminated timber--based construction enables better conditions for industrialized prefabrication, which can reduce related GHG emissions and on-site financial costs. In the light of "design for disassembly" principles, the option for industrialized prefabrication can thus offer waste reduction and further adds climate benefits at the end-of-life stage (Lehmann, 2013). Reduced waste and increased recyclability are however achievable for the wood-based construction types found in both the CLT and the ATF scenario. If considered properly during the building phase, wood-based construction thus allows in general for increased re-use potential of the renewable materials applied and by that improves the climate performance as well as other environmental indicators.

3.2.3. *Role of future wood-based dwelling size on the atmospheric temperature change*

Not only the choice of materials is of importance for enhancing environmentally sustainable housing construction. Another crucial aspect is the average dwelling size. The trend of larger dwellings contributes to higher environmental burdens (Ivanova and Büchs, 2022). Fig. 6 presents the change in atmospheric temperature induced by both scenarios when varying the current wood-based dwelling size by ± 20%. The temperature change is given in a relative sense, i.e., when benchmarked to the reference projection of concrete frame dominance in Swedish MFHC where the size of the dwelling remains stable, i.e., 57 m^2.

Decreasing the dwelling size from 57 m^2 to 45 m^2 increases the net climate cooling effect in both scenarios, while increasing the dwelling size to 68 m^2 reduces the net climate cooling effect. In fact, with a larger average dwelling size, the CLT scenario results in a slight net warming compared to the reference projection, i.e., the concrete frame dominated MFHC with 57 m^2. In contrast, an increased average dwelling size in the ATF scenario still produces a net climate cooling effect compared to the reference projection which is still slightly larger than the climate cooling effect of the CLT scenario under 57 m^2. A smaller average dwelling size is thus an additional important measure to reduce the climate impact, next to an increased wood-based construction.

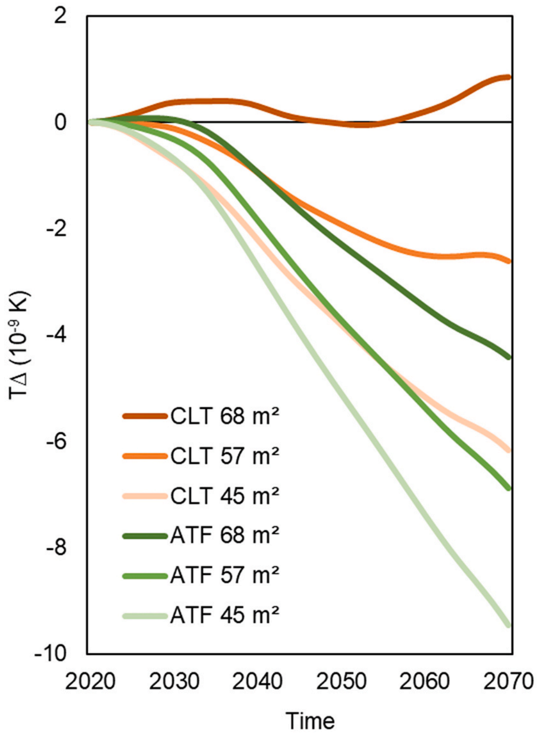

Fig. 6. Temperature change for the ATF and CLT scenario as compared to the reference projection, i.e., the relative change from a system perspective, and in dependence to a varying average dwelling size. ATF = average timber frame scenario, CLT = cross-laminated timber scenario. See Fig. 2 for details on scenarios.

It follows that a future MFHC applying the current wood-based construction types (ATF scenario) would be more climate beneficial than shifting to a cross-laminated timber-dominated MFHC, despite increasing the average dwelling size by 20%. In other words, a decreased dwelling size and extension of the timber light-frame dominated wood-based MFHC would maximize the climate cooling effect under the assumption of remaining on the middle-rise building level. As mentioned above this finding is mostly a result of the more efficient wood-use ratio in buildings based on timber light-frame in comparison to cross-laminated timber alternatives. A lower wood-use efficiency of the CLT scenario thus provokes a higher reduction in forest carbon due to increased harvest volumes required, as deducible from Fig. 5. In addition, the reduced wood-use efficiency is mirrored in the temperature change curves whose variation appears more pronounced for the dwelling size alterations under the CLT scenario compared to the ATF scenario.

A decreased dwelling size coupled with an increased wood use in MFHC would thus pose the most climate beneficial option, and also induce the least impact on local forests in terms of the risk of negative impacts on biodiversity. This combination of transforming the building stock into a more bio-based one together with the net saving of materials could thus add substantially to the so-called residents "handprint" potential due to the strong growth potential in residential carbon sequestration and storage capacities (Kinnunen et al., 2022). This would decrease the residents' usually heavy consumption-based lifestyle (Heräjärvi, 2019; Kinnunen et al., 2022) yet would require large and joint efforts from urban-planners, policy-makers, the scientific community, and the residents themselves (Kinnunen et al., 2022).

4. Conclusion

This study explores consequences of a complete replacement of concrete with different wood-based alternatives as frame material in Swedish multi-family housing construction (MFHC) from 2030. In addition to GHG fluxes and associated atmospheric temperature change, the study assesses implications as to the future state of Swedish forests induced by additional harvest volumes, notably in change of old forest area. Thereby we further the understanding of, firstly, the amount of wood that would be needed for completely substituting concrete in future MFHC in Sweden, based on an official housing demand forecast. Secondly, we estimate climate effects over time for different wood-based construction systems, as well as the role of dwelling size. Finally, we provide an assessment of climate-biodiversity trade-offs following increased wood use within a Northern European setting, using the indicator of change in the area of old forest.

The results show that the wood needed for the complete substitution of concrete as the — hitherto dominating — frame material in Swedish MFHC can be sourced entirely from national forests with only minor impacts on the forest carbon sink and the area of old forests. This holds true even considering the more wood-intense frame system solid cross-laminated timber. In addition, we find that a climate benefit of either -0.24 Mt CO_2 eq $year^{-1}$ for a timber light-frame or -0.09 Mt CO_2 eq $year^{-1}$ for a cross-laminated timber dominance is given, as compared to a continuation of the current concrete-dominated MFHC.

The timber light-frame system not only provides the largest climate benefit but also leads to the smallest reduction in the area of old forest.

In any case however, climate change mitigation from wood-based substitution comes with the trade-off of decreasing area of old forests. This is exacerbated using the cross-laminated timber system, due to a less efficient wood-use ratio per dwelling unit which also explains its inferior climate performance compared to the currently dominating wood-based construction type, timber light-frame. However, a ramp-up of the use of modern engineered wood product-based construction, notably cross-laminated timber, would expand the application range due to superior structural properties, thus further enabling substitution of concrete-based construction, e.g., in high-rise buildings.

Decreasing the average flat size in future wood-based MFHC by 20% yields additional climate change mitigation. The largest climate change mitigation is provided when smaller dwellings are built using the timber light-frame system. In contrast, MFHC with a 20% larger average dwelling size based on the cross-laminated timber system has a climate impact comparable with concrete-based construction with a current average dwelling size of 57 m^2.

Summing up, when aiming for increasing the share of wood-based construction, decreasing the average flat size would maximize not only the climate benefits, but would also minimize decline in old forest area, and reduce both urban and forest land use. To achieve this however, large, and joint efforts from urban-planners, policymakers, the scientific community, and the residents themselves are required.

CRediT authorship contribution statement

Maximilian Schulte: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Ragnar Jonsson:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Writing – review & editing. **Jeannette Eggers:** Conceptualization, Validation, Resources, Writing – review & editing. **Torun Hammar:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing. **Johan Stendahl:** Conceptualization, Validation, Resources, Writing – review & editing. **Per-Anders Hansson:** Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that the mutual funding by Swedish University of Agricultural Sciences and Stora Enso Oy may be considered as a potential competing interest.

Data availability

See Supplementary Material

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Appendix A. Supplementary data

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