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Full length article

Reducing the land-use impact of wooden buildings with fast-growing biobased materials: A Danish case study

Rasmus Nøddegaard Hansen [a,*], Endrit Hoxha [a], Harpa Birgisdóttir [a], Francesco Pittau [b]

[a] Department of the Built Environment, Faculty of Engineering and Science, Aalborg University, A.C. Meyers Vaenge 15, DK-2450 Copenhagen, Denmark
[b] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzo 31, IT-20133 Milano, Italy

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ABSTRACT

This study explores the potential of the reduced demand for land and increase in biogenic CO_2 storage for incorporating crop-based products in wooden buildings. It uses case studies to create a material-flow analysis of future Danish building stock with four market-implementation scenarios. Alternative biobased materials show reductions in the land requirements and improved CO_2 storage, especially for single-family and multifamily houses. This causes a decrease of 50–61 % in the use of wooded land. Danish straw can supply almost a 50 % implementation, rising to 100 % when combined with grass materials. Building designers and planners are encouraged to prioritize fast-growing biobased materials to minimize the requirements for land in wooden buildings. To achieve this, policy-makers should harmonize inclusive biobased building codes, upskill the workforce and financially support pre-approved solutions. Equally important is to investigate the cross-sectoral synergies between construction and agriculture to govern land for its enhanced environmental and social benefits.

1. Introduction

The building sector's worldwide impact on nature and climate through waste generation, natural resource consumption and greenhouse gas (GHG) emissions is stimulating increasing efforts to steer it towards improved environmental sustainability. This is becoming urgent because of the growing population and accelerating urbanization in Europe, but most profoundly in the Global South (United Nations, 2019). At the same time, Europe possesses examples of planning and creating liveable cities, as well as designing healthy and well-constructed buildings, which now need to be kept within the ecological boundaries (Andersen et al., 2020; Hansen et al., 2023). Essentially, this means reducing the environmental impacts of the region's activities. Not least, it is becoming imperative to come up with best practices that might also be useful in the Global South, since we have the financial, economic, educational and institutional capacity to take on that responsibility.

The aspiration to reduce the environmental impact of the building sector focuses predominantly on climate change. Here the main concentration is on the embodied climate impacts of building materials because the decarbonization of materials have not experienced the same improvements as the buildings' operational carbon emissions (Hoxha et al., 2017; Röck et al., 2020; Skillington et al., 2022). In recent years, this situation has led to a preference for wood with the potential to decarbonize the building sector due to its ability to sequester carbon during growth and store it, thus potentially acting as a carbon sink (Churkina et al., 2020). In evaluating the embodied carbon of wood in buildings, life-cycle assessments (LCA) are commonly used, which generally show more carbon reductions compared to buildings constructed of conventional materials when the analysis is made at the building project scale as opposed to the building-stock scale (Hildebrandt et al., 2017; Kayo et al., 2019; Amiri et al., 2020; Churkina et al., 2020; Lukić et al., 2020; Mouton et al., 2023).

Not many studies consider the dynamic timing of the biogenic carbon of wooden buildings in evaluating their carbon sink potential (Andersen et al., 2021), despite the dynamic methods developed for LCA by Guest et al. (Guest et al., 2013) and Levasseur et al. (2010, 2013). Meanwhile, Arehart et al. (2021) could be right to highlight our limited knowledge of the climate effects of assessing wood by dynamic LCA due to its carbon reducing potential's profound reliance on the substitution benefits. The consequential LCA findings in Hansen et al. (2024), where the climate impact is linked to the substitution effects of types of building

* Corresponding author.
E-mail address: rnh@build.aau.dk (R.N. Hansen).

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materials and wood co-products, support this. Furthermore, their identification of the sizeable impact of forest modelling on the potential for biogenic carbon storage makes it more complex to generalize about the climate benefits of wood. In addition, the availability of wood in a situation of increased demand is justifiably questioned by Pomponi et al. (2020), particularly if several sectors shift to biobased solutions because of the lengthy rotation period of trees, which requires long-term planning and adaptation to demand.

Regarding the complexities of the availability of wood and assessing biogenic carbon, two other interlinked challenges are connected to the shift to timber buildings, specifically its increased land-use impact (Allacker et al., 2014; Kayo et al., 2019; Lukić et al., 2020; Mouton et al., 2023), and the terrestrial biodiversity further down the impact pathway, which it also affects (Hansen et al., 2024). Nonetheless, few studies currently assess the land-use implications of increased wood in buildings (Göswein et al., 2021; Andersen et al., 2022; Mishra et al., 2022).

Andersen et al. (2022) conclude that the implications of a global change to cross-laminated timber (CLT) buildings for the transformation of our forests only requires a small percentage of the global forest area. The study contains a notable simplification of suitable tree species as construction timber and omits the existing demand for wood from the building and other sectors. Mishra et al. (2022) uses more advanced modelling of the climate impacts and land-use change of globally increasing wooden mid-rise dwellings to 90 % of the building stock. Despite the results showing low side-effects on agriculture and greater CO_2e reductions, the level of demand in this respect is causing the deforestation of primary forests. The integral question that arises is whether we want that to happen.

A study by Göswein et al. (2021) found that Europe has enough available wooded land to cover the regional demand for construction in Europe. Nonetheless, they failed to take all building elements into account by only considering roofs and external walls and restricting their investigation to the residential building stock alone. Moreover, to analyse the complete demand for timber in construction, the adopted forest model should include an increase in wood harvesting that is not used by other sectors while accounting for the annual growth in tree stock, which can result in the serious risk of decreasing the forests' overall carbon-uptake capacity. Interestingly, Göswein et al. (2021) identified fast-growing biobased materials as having a greater potential in being used in buildings because some appear to have plenty of available supply.

Individually these studies do not make a complete assessment of the building stock beyond the residential coverage of an entire building structure, nor do they conduct a wood availability analysis. In addition to the risk of degradation to primary forests identified by Mishra et al. (2022), the planetary boundaries of land-system change and biosphere integrity (biodiversity) are being transgressed (Richardson et al., 2023). This also emerges from a study linking timber consumption to the EU's Planetary Boundaries (O'Brien and Bringezu, 2017) and to the German bioeconomy safe operating space (Egenolf et al., 2022). This presents an imminent need to assess the wooden building stock more completely, as well as its potential land-use impact and reduction pathways beyond the one-dimensional climate-mitigating imperative. Here, fast-growing biobased resources are shown to be beneficial in facing the impacts of climate change and land-use. Göswein et al. (2021) highlight the potential of straw and hemp, while in Geß et al. (2021) grass insulation appear to reduce the effect for most impact categories compared to mineral wool.

On this basis, this study aims at a two-fold assessment: (1) investigating the potential for incorporating fast-growing biobased resources in wooden buildings through the substitution of non-loadbearing wood and insulation products, including straw, hemp and grass; and (2) upscaling the implementation of wood and fast-growing biobased materials to Denmark's building stock at four different market penetration rates, culminating in an evaluation of the potential land-use impacts and its supply covered nationally and imported to the Danish market. This suggests the following research questions:

1. What will the wooden building element archetypes and the future material demand look like when non-loadbearing materials are made of fast-growing biobased resources?
2. How will the implementation of fast-growing biobased materials in wooden buildings affect land-use and quantities of stored biogenic carbon towards 2050?

2. Methods

This methods section explains the material flow scenarios and the cumulative material demand, then follows the approach of linking the material demand to CO_2 storage, the required land-use and the availability of materials, as shown in Fig. S1 in the Supplementary Information Appendix A (SI) and the graphical abstract. In detail, the steps comprise: (1) making archetypes by substituting non-loadbearing structural wooden products, insulation and finishings in timber buildings for single-family houses, multifamily houses and office buildings with products derived from the fast-growing biobased resources of straw, hemp and grass; (2) modelling the building stock at four different market penetration rates for wooden buildings and the various scenarios of fast-growing biobased material substitutions; and (3) assessing carbon storage and land-use, together with their nexus, associated with the potential for using fast-growing biobased products in wooden buildings.

2.1. Material flow scenarios

The study uses three original case studies from Denmark to represent wooden buildings, the reference cases of the considered typologies being a single-family house, a multifamily house and an office. In these buildings, we explored the opportunities to replace non-loadbearing wood and insulation products with materials made from fast-growing biobased resources such as straw, hemp and grass by constructing new component archetypes, resulting in four different biobased scenarios. Afterwards, we applied these four scenarios to four different market penetration rate scenarios in 2050. The biobased and market penetration rate scenarios are presented in Table 1. It should be emphasized that all four biobased material scenarios contain wood, STR and GRA contain a low amount of hemp, and the GRA scenario uses grass for insulation and straw for non-loadbearing products. The market penetration rates range from the current rate for wooden buildings in Denmark (Lind and Damsgaard, 2021), i.e., a constant market penetration towards 2050 in scenario SC-11, to 100 % in scenario SC-100. The SC-11 market penetration rate is constant during the same time period, while SC-25, SC-50, and SC-100 are characterized by a linear annual increase towards 2050, starting at the current 11 % of market penetration. The combined biobased and market penetration rate scenarios can be linked by name: for

Table 1
Names of the scenarios for the biobased material alternatives and the market penetration rates. The individual name logic of the biobased materials are as follows: REF for the wood reference. The individual name logic of the market penetration scenarios are as follows: SC-11 for 11 %. The combined scenario name logic are as follows: REF11 for the wood reference with the 11 % market penetration. The 11 % market penetration rate in 2050 refers to the current market penetration of wood buildings in Denmark, i.e., is annually constant. The other market penetration rates in 2050 involve a linear annual increase of market penetration starting from the current market penetration of wooden buildings.

Market penetration rate \ Biobased material	Wood = REF	Straw = STR	Hemp = HEM	Grass = GRA
11 % (current) = SC-11	REF11	STR11	HEM11	GRA11
25 % = SC-25	REF25	STR25	HEM25	GRA25
50 % = SC-50	REF50	STR50	HEM50	GRA50
100 % = SC-100	REF100	STR100	HEM100	GRA100

example, the wood reference scenario at the current market penetration rate is called REF11 (see Table 1).

The derived material intensities in kg/m^2 gross floor area (GFA) of the combined biobased material and market penetration rate scenarios were created to material flow scenarios using the area forecast in m^2 GFA of Hoxha et al. (2024) for the years 2022–2050. This is a spatio-temporal prognosis based on the Holt-Winters additive method, which is a useful forecast method when having historical times series. It uses level, trend, and seasonal components to forecast building activity onwards from where the time series end. The level is the area starting point from where the subsequent year's area is forecasted based on the trend i.e., the aggregated historical trend based on previous construction activity. The seasonal component then corrects for cyclical tendencies in the historical data series. Thus, it identifies historical trends and cyclical movements to model an area prognosis on that basis. The referenced study forecasted the demand for seventeen building typologies and analysed the needs for future materials in the case of a business-as-usual (BAU) construction scenario. Our study resulted in sixteen cumulative material demand scenarios in Mt material quantities. Our assessment considers the production stage (A1-A3) of the demand for materials according to EN 15978 (2012), but not the need for replacements during the life-cycle.

2.2. CO_2-storage and land-use

The wooden and fast-growing biobased resources sequester carbon as they grow, which can be stored in the buildings themselves by being present in its materials. However, not all the resources from the land will be used for building materials, since losses occur during the harvest and product processing. Therefore, this study only accounts for the stored CO_2 in the final building products, *excluding* the losses, but it attributes all the land used to the respective building products, *including* the losses.

2.2.1. CO_2-storage accounting

The stored CO_2 was calculated using the individual products' biogenic carbon content, converting it with reference to the molecular weight ratio between carbon and CO_2. The data mainly came from environmental product declarations (EPD); if they were unavailable, we used the manufacturers' technical data sheets. Some EPDs or technical data sheets had information on the biogenic content per declared unit. Products without that information were calculated as a multiplication of the product density, biogenic dry matter content as a weight percentage and biogenic carbon content in the biogenic dry matter (assumed to be 50 % for all products). The plywood and chipboard biogenic CO_2 content is 1.52–1.54 kg CO_2/kg dry-matter material. The equivalent oriented straw strand board (OSSB) of straw and hemp is 1.42 and 1.56 kg CO_2/kg dry-matter material respectively. The insulation biogenic carbon content for paper wool is 1.56 kg CO_2/kg dry-matter material, while loose straw, hemp and grass insulation have 1.29, 1.26, and 1.50 kg CO_2/kg dry-matter material respectively. The straw and hemp batts insulation contain 1.42 and 1.26 kg CO_2/kg dry-matter material respectively. All data and references are presented in SI Section 3.1.

2.2.2. Availability: harvesting and land-use accounting

Harvesting timber involves roundwood logs being transported to a sawmill, where they are debarked and reduced to sawn timber, followed by kiln drying and finally being put through a planing process making the sawn timber suitable for construction. This results in a loss factor of 2.94 from forest to building product, meaning 2.94 m^3 timber input per 1 m^3 output product (Göswein et al., 2021). For wooden oriented strand board (OSB) and chipboards, we calculate roundwood transported to the sawmill and processed, 1.52 m^3 input being needed to produce 1 m^3 of output product (Göswein et al., 2021). For all other products, we assume a 5 % loss from harvesting or waste collection, including the production of fast-growing biobased materials (Göswein et al., 2021).

The previously derived cumulative demand for materials, including losses, was linked to availability and land-use using Statistics Denmark's tables (Statistics Denmark, 2023a, 2023b, 2023c) of national supply. For international supply, wood data came from Forest Europe (2020) (see SI Tables 6 and 7), hemp data from EUROSTAT (see SI Tables 11 and 12). To consider likely trading partners for Denmark, the international supply was confined to a "market for Denmark" based on a Danish wood consumption footprint within the EU member states in EXIOBASE 3.8.2. (Stadler et al., 2018, 2021), namely Estonia, Finland, Germany, Latvia, Poland and Sweden.

The availability of the four biobased resources and their associated requirements for land were first calculated and defined for Denmark in two categories: (1) the national land available for construction; and (2) the national land available. The first entails resource availability which is not demanded by other industries, i.e., is free to use. The second comprises the total resource availability in Denmark where some land is already being used by other sectors. Where Denmark's production cannot supply the demand, we calculated the available land for the respective resources needed to be covered by the market for Denmark and defined in two categories: (1) covered by "market for Denmark" land available for construction; and (2) covered by "market for Denmark" land available. They were calculated for wood and hemp materials.

Straw and grass are already available to a certain extent in Denmark. The land needed for wood in all scenarios was modelled as the cumulative land needed from 2022 to 2050 because the rotation of trees, commonly 80–100 years for coniferous forests (Masera et al., 2003), are longer than the period considered in this assessment for the upfront demand for materials. The land needed for fast-growing biobased resources was calculated according to the year corresponding to the maximum material demand, with a short rotation period assumed to be equal to one year. For STR50 and STR100, 2050 resulted in the most demand for land, whereas it was 2044 for STR11, STR25, and all HEM and GRA scenarios. Fig. 1 shows the availability of timber, straw and grass by region in Denmark.

Wood

To calculate the availability of wood in Denmark by harvest in cubic meters and land in hectares (10,000 m^2), this study used data from Statistics Denmark's Tables SKOVRG01 (2023c) and SKOVRG03 (2023d). It used the years from 2015 to 2020 to calculate the period's average harvest and land-use of coniferous wood. We only considered coniferous wood because this softwood is what is most often used in construction (Göswein et al., 2021). The average yield per year was assessed at 9 m^3/ha. The national land available for construction was considered the net change in the annual forest stock, since this is what is available after the demand from other sectors. The annual growth of Danish coniferous forests was used for the potential national land available if no other sectors used the wood.

In addition to the availability of wood in Denmark, we calculated the availability of wood in the market for Denmark using Forest Europe (2020) data from 2015. For missing data on Latvia and Poland, the information for 2010 from Göswein et al. (2021) was applied (see SI Tables 6–10). The land available for construction was derived by subtracting fellings in forests available for wood supply from the net annual increment in forest available for wood supply. The land available was considered equivalent to the net annual increment. The weighted average yield of the market for Denmark is 5.82 m^3/ha. The weighting was based on the share of the land area of forest available for wood supply in each supplying country (SI Table 6, column 6). The weighting factors for each country are presented in SI Table 7.

Straw, hemp and grass

The average harvest and land-use values for all three fast-growing biobased resources were calculated based on the years 2015–2020 for Denmark and 2014–2022 for the market for Denmark (only hemp). The straw harvest and land-use in Denmark were calculated using Table HALM1 of Statistics Denmark (2023a). Straw is already partly used for energy, fodder and bedding, while some is left on the field. We

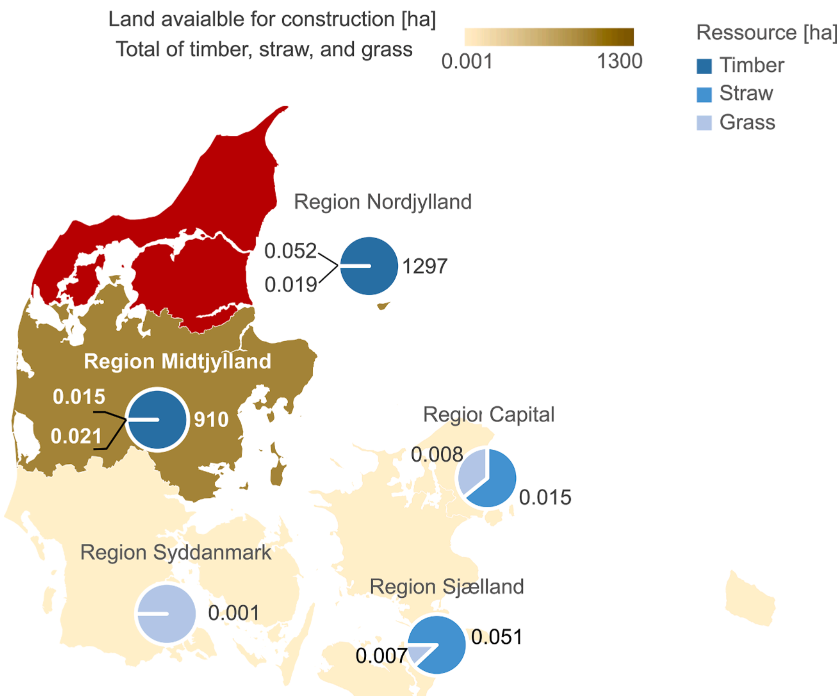

Fig. 1. The area of land available for construction per year for timber, straw and grass in Denmark's five regions (in hectares). The figures are averages between 2015 and 2020. The pie charts detail the availability of land for construction of the three listed resources.

assumed that 33 % needs to be left on the field to leach nutrients back into the soil (Göswein et al., 2021). The national yield was calculated at 3.7 t/ha. Since Denmark's national land available for straw production is sufficient to meet the demand for construction, the market for Denmark for straw is not treated further here.

Hemp is not produced in Denmark, so we consider only the two types of market for Denmark land. The countries in the market for Denmark producing hemp include Poland, Finland and Latvia regarding land-use. However, we lack data on the harvest from Finland, meaning it is left out of the yield calculation, which results in an average yield of 6.1 t/ha.

We used Statistics Denmark's Table HST77 (2023b) for grass, including permanent and temporary grassland. All national harvested grass is used for fodder. Despite this, only about one-third-of the permanent grass is used, leaving a sufficient quantity for construction in Denmark. The average yield amounts to 45 t/ha.

3. Case buildings and archetype development

This study uses three case buildings, one for each building typology: single-family house (SFH), multifamily house (MFH) and office building (OB), since they represent >80 % of the expected newbuild area in the future (Hoxha et al., 2024). The components taken into account in exploring substitution opportunities comprise floors, internal walls, external walls and roofs. As SFH only has one storey, floors are not investigated for that building typology. The MFH and OB case buildings represent the actual REF scenario, but for SFH we partly constructed the REF since the available case building already had straw insulation in its exterior walls. Hence, the external walls were reconstructed to contain paper wool as insulation in the REF.

To develop archetypes for STR, HEM and GRA, the insulation U-value should be equal to the REF scenario. In components where STR, HEM and GRA led to increased or decreased insulation thickness, the thickness of the loadbearing wood structures, such as studs, joists, beams or columns, was consequently adjusted. The thickness of all other building products in the respective components was assumed to equal the thicknesses in the REF. See SI Section 3 for materials, quantities and archetype section drawings.

4. Results

4.1. Biobased material demand

The material stock across the three building typologies for each scenario of biobased materials at different market penetration rates is presented in SI Figure 7. The figure shows the stock of only the biobased materials. The current market penetration rate results show a building-stock development aligned with the forecast area development. The total built area in 2050 accumulates to 134.2 million m^2. For the 25 %, 50 % and 100 % market penetration rates, we see increases towards 2050 with cyclical peaks (local maxima) in 2030, 2044 and 2050. STR results in the largest material demand in all market penetration scenarios, followed by GRA, HEM and REF. In general, 2044 will have the greatest material demand for most biobased materials and market penetration scenarios combined, but for REF50, HEM50 and GRA50 it will be 2050. The parameters influencing the demand for materials in each year are the total forecast area across the three building typologies, material intensities of the respective building typologies and the market penetration rate. The area forecast drives the demand for 2044, the year with the greatest area, and the market penetration scenarios do this for 2050 due to the linear increase towards this year. Combining them shows that the area forecast is the main factor across most biobased market penetration scenarios. However, the 50 % market penetration rate is the main factor for that scenario rate for all the biobased scenarios except STR. The figure does not give the total compound material requirement, so we will turn to the results of a cumulative material demand to calculate the quantity of materials needed in the different scenarios.

The cumulative material demand in SI Figure 8 shows the material distribution of the three building typologies and the share of biobased resource types in the four scenarios. Wood is the only biobased material present in the REF scenario, where it ranges from 2.2 to 12.3 Mt employed material depending on the market penetration rate. It is distributed almost equally among the building typologies from SFH to OB at 31 %, 29 % and 39 % respectively. The most interesting aspect of the figure is the remarkably greater use of straw in terms of mass in SFH and MFH in STR compared to the hemp and grass scenarios. Straw replaces a large quantity of wood products and insulation in the SFH (21 %) and MFH (20 %) scenarios, but considerably less for OB (5 %). Although fibre-reinforced clay boards contain hemp, the quantity seems negligible in STR. The total material demand in STR increases from 3 Mt material at the current market penetration to 16.4 Mt material at 100 % market penetration.

For the hemp-based scenario, HEM, the greatest substitution rate appears for MFH regarding mass at 13 %, followed by SFH at 8 %. Finally, a very low substitution rate of 3 % occurs for OB compared to the two other building typologies. The cumulative material demand ranges from 2.4 to 13.3 Mt.

In GRA, or grass, only insulation leads to SFH (5 %) having the largest substitution rate, followed by MFH (4 %), while being negligible for OB (1 %). The other products were considered as in the STR scenario. Therefore, a greater incorporation of straw emerges in MFH while being less in SFH and OB. The cumulative material demand in GRA is between 2.6 and 14.1 Mt.

4.2. Biogenic CO_2 storage development

Further analysis of the cumulative CO_2 storage in Fig. 2 showed that the material demand in STR also causes the largest biogenic carbon storage for all four market penetration rates. The cumulative 15.7 Mt CO_2 storage in STR100 increases to almost double the 8.4 Mt CO_2 storage in REF100 in 2050. The implementation of hemp and grass in HEM100 and GRA100 results in 12 and 13.1 Mt cumulative CO_2 storage in 2050, approximately midway through the storage amount of REF100 and STR100.

In comparison, the cumulative CO_2 storage at the current market penetration rate in 2050 causes the storage in STR11 to develop to 3 Mt CO_2. Again, it remains nearly double the REF11 of 1.6 Mt CO_2. HEM11 and GRA11 appear to store 2.3 and 2.5 Mt CO_2 respectively. The results generally indicate that using straw, hemp or grass leads to greater cumulative CO_2 storage by wooden buildings.

The origin of the CO_2 storage in the REF, as shown in Fig. 3, comes from wood and mostly occurs in SFH at 41 %, followed by 34 % for OB and 26 % for MFH. The distribution of the building typology changes, notably for OB and MFH in STR, where the total share of the former decreases to 26 % and the latter increases to 35 %. SFH decreases a little to 39 %. The straw materials contribute the greatest to CO_2 storage for SFH and MFH, which is still wood for OB. The CO_2 storage in the hemp in the fibre-reinforced clay boards turns out to be negligible.

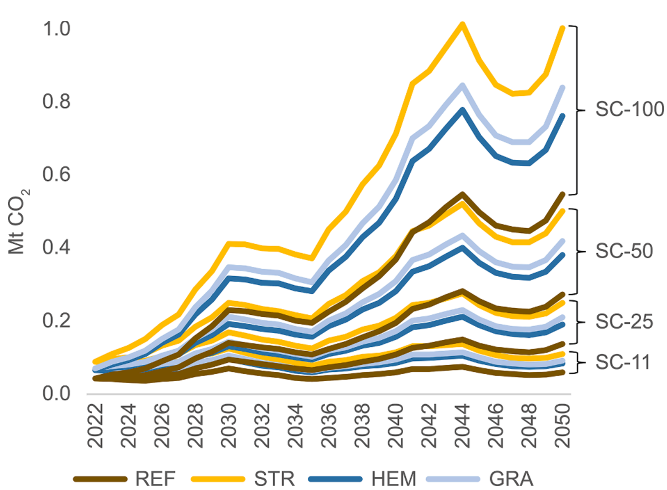

Fig. 2. Annual CO_2 storage development during 2022–2050 for four biobased scenarios and four market penetrations. The market penetration rates show a linear increase towards 2050 from the current level. Biobased scenarios: REF=wood reference, STR=straw, HEM=hemp, GRA=grass. Market penetration scenarios: SC-11=11 %, SC-25=25 %, SC-50=50 %, SC-100=100 %.

The total share of CO_2 storage in HEM for SFH decreases slightly to 39 % and in MFH to 32 % compared to the STR scenario, while OB increases its share to 29 %. The wooden materials in SFH and OB provide the greatest CO_2 storage, but hemp also contributes notably to SFH. By contrast, hemp provides the most CO_2 storage in MFH, responsible for about two-thirds of its storage.

In the last scenario, GRA, OB's total share of the storage, is nearly unchanged at 28 % compared to HEM, and similar for SFH, which slightly increases its share to 41 %, while MFH decreases its CO_2 storage share to 31 %. Once again, wood provides the largest CO_2 storage with both SFH and OB. For the former, grass is second in terms of CO_2 storage, followed by straw. Grass provides little CO_2 storage in OB, thus the second largest comes from the straw. Conversely, straw provides the largest storage potential in MFH, followed by wood, but grass also delivers notable CO_2 storage at a slightly lesser quantity than it does for SFH. However, with the increase in CO_2 storage through the use of fast-growing biobased materials, we need to understand whether storage is available and where in order to scale up its use in the building sector. This is considered in the next section.

4.3. Resource availability and land-use impact

As a starting point, SI Figure 9 illustrates the resource availability equivalent to the share of land in Denmark and the market for Denmark for the four biobased scenarios at the four different market penetration rates. When the market penetration rate increases, the share of land and resources covered outside Denmark increases with it. All three fast-growing biobased material scenarios increase the supply covered by Danish land by a factor of about 2 to 4, hence reducing the need to import resources.

The grass in GRA has the largest national availability, whereas Denmark's supply at the current market penetration rate, SC-11, can cover >50 % through direct availability for the construction sector. For the SC-25 market penetration rate, >30 % is covered by the national availability of land, while it falls below 18 % for the SC-50 and SC-100 market penetration rates. Around 45 % of the land needed in the straw scenario, STR, will be available in Denmark at the current market penetration rate, SC-11, and remains at about 25 % for the SC-25 market penetration. The SC-50 and SC-100 market penetration rates are lower than 15 % of what can be covered by the national land available for the building sector. The HEM scenario needs the most supply from the market for Denmark among the fast-growing biobased material scenarios. About 30 % is available in Denmark at the current market penetration rate of SC-11, and approximately 18 % in the SC-25 scenario. The two largest market penetration rates see <10 % covered by the Danish supply. Now that we know the fast-growing biobased resource scenarios can increase national availability and land-use, we need to understand better the land-use impact of such implementations and more insights specific to the studied resource types of wood, straw, hemp and grass.

4.4. Land-use and availability for each resource type

Fig. 4 analyses the land-use impact of the different scenarios per resource type, what is currently available in Denmark for construction, and what could be available if not in demand by other sectors. If Denmark cannot completely supply a resource, then the figure also gives information on the share of that resource covered by the market for Denmark. The most striking result to emerge from the data is that the land-use impact of wood is roughly halved for all three fast-growing biobased materials (Fig. 4a). However, Denmark can still not fully supply the wood needed in any scenario, not even at the current market penetration rate. The market for Denmark has substantial wood resources available for construction for the fast-growing biobased material scenarios, i.e., more than a factor of 100 in the 100 % market

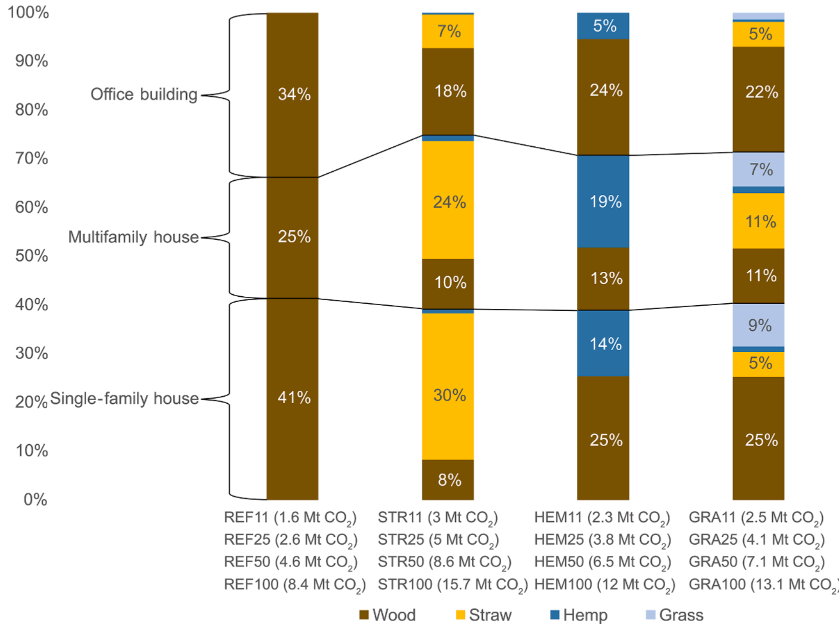

Fig. 3. Cumulative CO_2 storage in 2050 separated by building typologies and biobased resource types, i.e., total material needed in 2022–2050. The bars show the share of CO_2 storage by resource type. The numbers in brackets on the first axis show the absolute cumulative Mt CO_2 storage of the biobased materials for all scenarios. Multiplication of the share (%) with the horizontal axis values yields the CO_2 storage by resource per scenario. Biobased scenarios: REF=wood reference, STR=straw, HEM=hemp, GRA=grass. Market penetration rates in 2050 in %: current (11), 25, 50, 100.

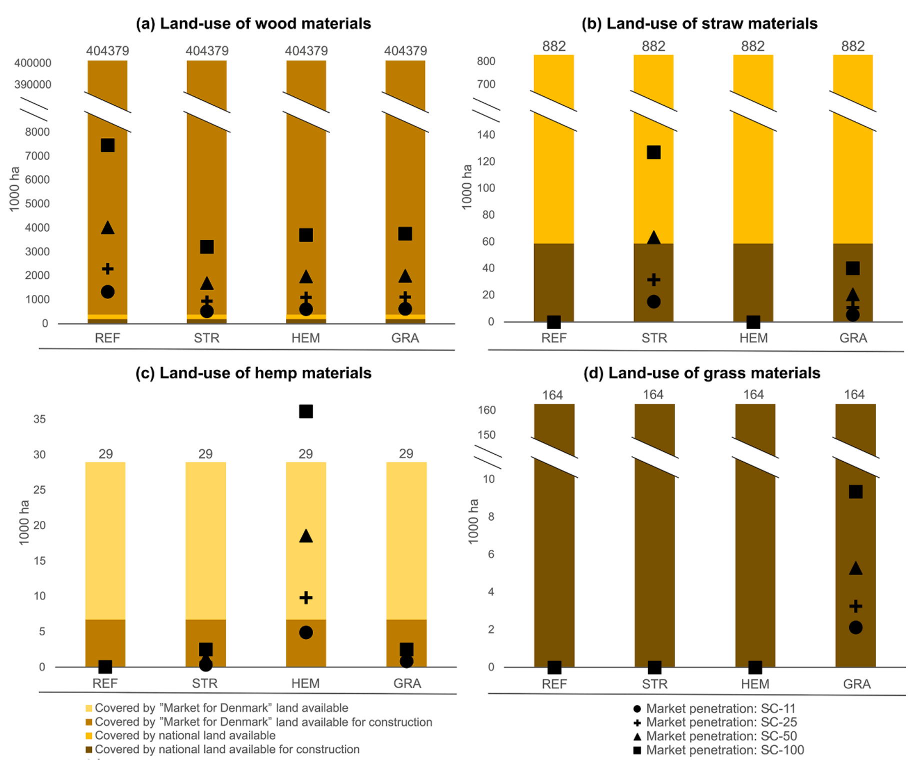

Fig. 4. The dark blue markers show the land-use impact for each of the four biobased materials, demanded in the four biobased scenarios and the four market penetration rates in 2050, figure (a)=wood, (b)=straw, (c)=hemp, (d)=grass. The bars show the land available in Denmark (national) and the 'Market for Denmark' through two definitions: (i) land available for construction and (ii) land available, meaning it is used by other sectors as well. The 'Market for Denmark' land is only presented if Denmark's supply cannot cover the demand. REF=wood reference, STR=straw, HEM=hemp, GRA=grass. Market penetration scenarios: SC-11=11 %, SC-25=25 %, SC50=50 %, SC-100=100 %.

penetration scenario.

Delving into the straw resources in Fig. 4(b), considered in STR and GRA, the current unused supply of straw can meet the demand for the current and 25 % market penetration rates and almost for the 50 % scenario. Other sectors use more than half of the land for straw production needed for a 100 % scenario. In GRA, the demand for straw can be met for all market penetration rates.

The situation is different for the hemp resources in HEM in Fig. 4(c), where the absence of production in Denmark requires using land abroad. The land available to supply hemp for construction in the market for Denmark can only provide enough hemp at the current market penetration rate. HEM25 and HEM50 are available but entail competition with other sectors' requirements, while the 100 % scenario needs more land than is available in the market for Denmark. In contrast, the market for Denmark can supply the hemp for the fibre-reinforced clay boards for STR and GRA for all market penetration rates.

The grass only pertains to GRA, of which the Danish national supply available for construction remains enough for the demand imposed by all the market penetration scenarios. The 100 % market penetration rate in GRA is as much as sixteen times below the capacity of the current national grass supply.

4.4.1. Land-use and CO_2 storage indicator

As the benefits of fast-growing biobased materials appear to exist by virtue of the increased CO_2 storage and reduced land-use impact, the indicator of hectares of land-use per ton of CO_2 storage illustrated in Fig. 5 supports that evidence for all three building typologies. The indicator deviates insignificantly from the market penetration rate. The greatest reduction of land per unit of CO_2 storage in relative and absolute numbers occurs for the SFH, with the straw scenario showing the lowest factor, followed by the hemp and grass scenarios. The reduced land-use per unit of CO_2 storage in these scenarios compared to the REF scenario extends about 4.5 to 10 times lower. The increased use of fast-growing biobased materials in MFH results in a factor 3–5 reduction to the indicator compared to the REF, where the straw scenarios again cause the lowest factor, followed by the grass scenarios and, eventually, the hemp scenarios. OB shows less than a factor of two decrease in the indicator in the fast-growing biobased material scenarios compared to decreases for SFH and MFH. The order of biobased material scenarios with the lowest land use-CO_2 storage indicators for OB are equivalent to MFH, i.e., STR, GRA and HEM.

4.4.2. Land-use per m^2 gross floor area

Increasing the insights and usefulness for planners, the focus now centres on land-use per m^2 GFA. SI Figure 10 presents those results for the three building typologies for all biobased materials and market penetration scenarios. There is a considerably positive causation between using fast-growing biobased materials and reducing land-use per m^2 GFA for SFH and MFH, where the requirement for land, both relatively and absolutely, declines notably with increasing market penetration rates. In comparison, using fast-growing biobased materials in OB has a smaller land-use reduction, where STR has almost the same land-use as REF except for the scenario of the current and 25 % market penetration rates. Thus, only hemp and grass result in the small land-use reductions for OB.

For SFH, STR results in the largest land-use reduction: in the 100 % market penetration scenario, it is 1.6 times lower than HEM and 1.7 times lower than GRA. The factor difference of land-use reduction per m^2 for SFH in STR compared to the REF extends from 6.2 at the current market penetration rate to 5.5 at the 100 % market penetration rate. However, despite the lower land-use reductions in HEM and GRA, these scenarios still result in substantial reductions compared to the pure wood scenario of REF. The land-use reductions for MFH are different, with the grass scenario leading to the largest decrease, followed by hemp and straw. Despite this, the relative differences in reductions between the three fast-growing biobased material scenarios are small compared to the situation for SFH. The reduced land-use factor from the REF to the GRA is 1.5–1.7, so there is still quite a notable decrease with all the fast-growing biobased materials.

4.4.3. Land-use per m^2 building element

The final disaggregation converges on hectare land per m^2 building element for the three building typologies, which could be useful information for building designers. SI Figure 11 shows that land-use differs remarkably depending on the building typologies, building elements and biobased material scenarios. The roofs of the SFH have their lowest land-use impact in GRA at $7.0 \cdot 10^{-3}$ ha/m^2; the land needed in STR and HEM is 1.2 to 1.5 times greater with 9.0 and $10 \cdot 10^{-3}$ ha/m^2. The external walls result in the lowest amount of required land in STR with $10 \cdot 10^{-3}$ ha/m^2, where HEM and GRA have 1.6 and 2.6 times greater impacts respectively. However, the roof and external walls substantially reduce the fast-growing biobased material scenarios compared to the wooden reference. The internal walls increase the impact because the reference case only contains unfired clay bricks and other inorganic materials.

The roofs of the MFH show the largest decrease in land-use impact in HEM, of $3.0 \cdot 10^{-3}$ ha/m^2, compared to the wooden REF, at $3.1 \cdot 10^{-2}$ ha/m^2, while STR and GRA require slightly more land at $4 \cdot 10^{-3}$ ha/m^2. The fast-growing biobased materials also result in reduced requirements for land for floors with $7 \cdot 10^{-3}$ ha/m^2 in STR and GRA, $8 \cdot 10^{-3}$ ha/m^2 in HEM, and $1.0 \cdot 10^{-2}$ ha/m^2 in REF. The external walls need 0.010 ha/m^2 in REF, HEM and GRA, increasing in STR to 0.012 ha/m^2. The internal walls lead to a slightly larger land-use impact for fast-growing biobased materials in STR and HEM compared to the wooden REF and GRA, which need the same area of land.

For OB, the required land for floors and external walls is reduced for the fast-growing biobased material scenarios compared to the REF scenario, but quite trivially. The internal wall reduces the required land from $1.9 \cdot 10^{-3}$ ha/m^2 in REF to $1.6 \cdot 10^{-3}$ ha/m^2 in the STR scenario, whereas it rises to $2.3 \cdot 10^{-3}$ ha/m^2 in the HEM and GRA scenarios. At the same time, the roof slightly increases its impact for all fast-growing biobased material scenarios, ranging from 6.19 to $6.24 \cdot 10^{-2}$ ha/m^2 compared to the $6.17 \cdot 10^{-2}$ in REF.

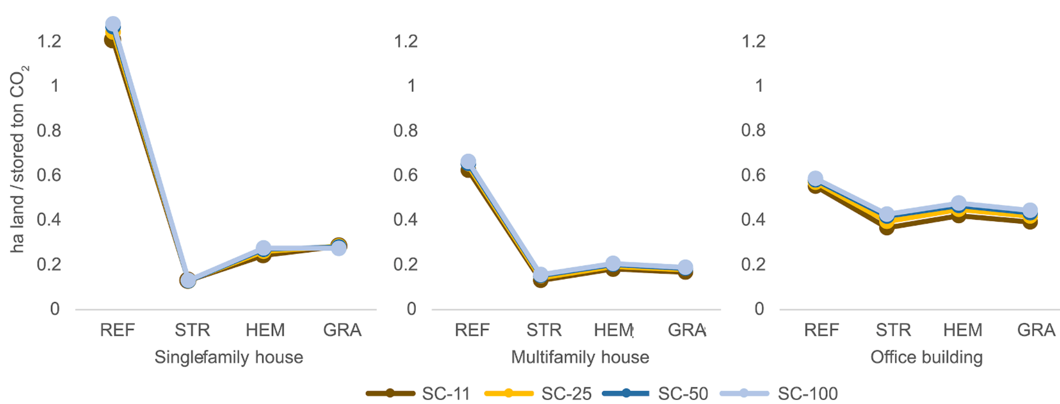

Fig. 5. Indicator of average land-use impact per stored ton CO_2 for the three building typologies for the four scenarios of biobased materials and four market penetration rates in 2050. Biobased scenarios: REF=wood reference, STR=straw, HEM=hemp, GRA=grass. Market penetration scenarios: SC-11=11 %, SC-25=25 %, SC-50=50 %, SC-100=100 %.

5. Discussion

5.1. Forests, climate mitigation and sustainability

Historically in Europe, forests, and specifically managed forests, have functioned as a fuel source for production and heating and as a construction material. However, forest management goals can provide various ecosystem services, from habitat functioning as a sustaining biological and genetic process for adequate biodiversity, to regulating the ecological processes of biogeochemical cycles for carbon storage, air quality and freshwater rinsing. Forests also provide the cultural functions of recreation, education and science, along with provisional services in the supply of fibre, pulp, timber and other raw materials. A forest can often provide more benefits, but trade-offs may also occur.

The intensive forestry in northern Europe focusing on provisional services entails high harvest rates, which leads to great levels of carbon sequestering compared to older forests because the tree harvest occurs before the forest and trees mature into a relatively steady state regarding carbon uptake and release (Duncker et al., 2012). Therefore, managed forests come with climate mitigation benefits. However, the monocultural character and intensity of harvests compromise other sustainability aspects, such as biodiversity functions and the regulation of groundwater and air. In addition, intense forestry on soil that is not very nutrient-rich will deplete its nitrogen, calcium and manganese content over time (Duncker et al., 2012). Thus, it requires increased fertilization, which is known for its high fossil-fuel consumption (Bajan et al., 2022). On the other hand, one study shows that forestry with provisional services can go together with biodiversity habitats and regulatory functions in practicing retention forestry (Jalonen and Vanha-Majamaa, 2001), which Gustafsson et al. (2012) and references therein underline for boreal and temperate forests. This is further supported by the findings of temperate forest simulation research (Duncker et al., 2012; Blattert et al., 2023). Thus, multifunctional forest benefits might not represent a large compromise in future silvicultural systems.

In addition to the CO_2 sequestration that intensive forestry provides, the climate mitigation effect might increase if the timber products displace the embodied carbon-intensive building products of concrete, steel and bricks (Lippke et al., 2011; Hansen et al., 2024). Because intensive forestry compromises other forest and sustainability objectives and the low utilisation quantity of original roundwood being turned into sawn wood (41–63 %) (Clark et al., 2010), it is conceivably not desirable to aim solely at intensive forestry. Since wood products may mitigate CO_2 by replacing load-bearing steel, concrete and bricks in buildings, wood should be used wisely for these building functions. Using the products of fast-growing biobased resources as an alternative could fulfil this wise use of resources in the building's structural but non-loadbearing functions.

5.2. The potential of fast-growing biobased resources in buildings

Very little was found in the literature on the question of the increased use of fast-growing biobased products in wooden buildings as a part of or a replacement for insulation, gypsum board and non-loadbearing wood products. Göswein et al. (2021) previously found that the availability of wood and straw could meet the expected demand for future European renovations and new housing. Their study only considered the material demand at a coarser aggregation for the archetypes of roofs and exterior walls. The investigation in our study details the building archetypes for all components and assesses the demand from Denmark's national perspective.

The present study found that fast-growing biobased products of straw, hemp and grass reduce land-use occupation when substituting insulation, gypsum boards and wooden products in single-family houses, multifamily houses and office buildings. Although the demand for wood decreases in the fast-growing biobased material scenarios, most of the required wood and associated land-use still occur outside the borders of Denmark. This also applies to hemp, which, on the other hand, could grow on Danish land if agriculture took up less area. Straw supply can be covered by straw's current unused availability except for the 100 % market scenario, whereas grass production is sufficient for all scenarios. Thus, the latter two are the two most promising among the scenarios we studied from the availability point of view.

There are two likely causes for the reduced occupation of land in the fast-growing biobased scenarios. First, the loss factor of producing sawn timber from debarking, drying and planing is significantly greater (2.94) than that from fast-growing biobased products, assumed to be 1.053. At the same time, OSB and chipboards have a loss factor of 1.52. Hence, all the land-use associated with processual losses is also ascribed to the final products. Second, we assessed the cumulatively needed land-use for wooden products over the 28 years of the forecast since trees' rotation rates are assumed to be longer than this period. The fast-growing biobased resources only have a rotation of one year (or less); hence, the study assesses their land-use as the year with the greatest demand for such products.

Another compelling finding is that the fast-growing scenarios considerably reduce the land-use per stored ton of CO_2. Furthermore, there is a slight increase in total CO_2 storage for an increased use of straw, hemp or grass, despite the reduction in the use of wood. This result is attributed to the fact that the fast-growing biobased products displace wooden products and mineral-based products such as insulation and gypsum boards. In contrast, wood products might bind more carbon than fast-growing biobased products for the equivalent volume, which requires more land because it takes time to regrow trees.

5.3. Cultivating our land-use for the planet and the people

The striking finding of the potential for reducing land-use by implementing fast-growing biobased materials in both wooden and conventional buildings holds out great promise. However, it also opens up a debate on how we want to use our land and for what purposes. There is an increasing interest in wood from different sectors, and the competition for land is steadily increasing due to global population growth. If straw, in some market scenarios, and hemp were used in Denmark's construction industry, other sectors, such as the agricultural sector, would need to reduce their land-use. In addition, the new EU Nature Restoration Law specifies that at least 20 % of terrestrial land needs to be returned to be wild nature by 2030 (European Commission, 2022). This would put more pressure on the land available for provisional uses.

Instead of thinking one-dimensionally about competition, Denmark could explore national synergies between the construction and agricultural sectors for added social value. One example would be an arrangement whereby the construction industry collaborates with farmers to transition to a more vegetable-based form of agriculture and then to produce crops for purchase by the construction sector. That might require policy support and collaboration by sector associations where economic packages and funds subsidize pilot projects. Finding new ways of using left-over straw from cereal production in buildings could lead to a higher economic output for farmers around the globe, coupled with the reduced demand for land from wood, which supports food security twice over.

In addition, the fast-growing crops we examined were assumed to have a rotation period of one year. However, it would have been useful to elaborate on this study by assessing whether different crops can share the same land area but at different times of the year without depleting the soil's carbon and nutrients. Also, there is already a potential for including grass harvesting in currently neglected areas such as airport runways, roadsides and household garden grass collection.

Integral to this study is the fact that it only considers environmental improvements on the supply side of the economy, showing that crops have a great potential for reducing land-use impacts, but not showing whether the pressure on land remains unsustainable. Therefore, reducing the forecast building area used in this study could be necessary to reach sustainability, not least by crucially focusing on avoiding the rebound effects for all building-sector actors, from designers to policymakers, as it always or at least often occurs when resource use improves. Here, it would plausibly mean increasing the building area or the inefficient use of materials because individual building projects' environmental footprints could be considerably reduced to its counterparts when integrating crop-based products.

5.4. Barriers to and opportunities for using fast-growing biobased materials

Hemp production still has large regulations for unwanted purposes. It is vital to reform these regulations so that hemp production can be increased for use in building products, especially since hemp also seems to have a moderate greater average yield in the market for Denmark, of 6.1 t/ha (SI section 3.4.), than the average yield of straw produced in Denmark, namely 3.7 t/ha. Also, the technical solution of using straw, hemp and grass products needs more widespread approval so that their practical use in buildings can increase. The obstacles include the thermo-physical properties of moisture and the avoidance of glue compounds with negative effects on the indoor environment. In addition, fire safety and acoustics also need appropriate design and use. It is not that the solutions do not exist, but rather that new sets of competencies from architects to construction workers need upskilling, the financial support of pre-approved solutions, and reviewing and adapting regional and national building codes to increase viable implementation. Rethinking buildings and architecture into more vernacular situations could be the creative challenge, both technically and aesthetically, that also sets fast-growing biobased materials free for the embodied craft that increases the longevity of the buildings. In that context, attitudes should change from material abundance to designing buildings with the available regional materials.

5.5. The study's limitations

This study does not account for indirect land-use change (iLUC). Still, as the assessment shows, fast-growing materials take up remarkably less land and have considerable availability; they might also reduce iLUC and the competition for land when decreasing the use of wood. However, it is important to be aware that straw is a byproduct, a non-determining product, whereby the demand for cereals determines the quantity of available straw. At present there is plenty of unused straw in Denmark, and with the increasing global population driving food consumption, the demand for it seems unlikely to fall on a large scale; thus, our approach must be considered conservative. Even if demand decreases, other crops can be grown to meet the demand from the building sector because the short rotation period makes it temporally easier to adapt to the altered demand.

The study only uses one building for each typology, which does not necessarily represent the current and future building stock very well. However, the relative differences between the scenarios can still bring useful insights for designers and urban planners. The overall resource demand and availability might vary if we included a larger case-study sample. Still, the findings stand out as suggesting reducing land-use by using the already market-ready products of fast-growing biobased resources. Also, as it takes time to implement these novel technologies in the building sector, the further examination of more building typologies and pathways for best practices of using fast-growing biobased materials can develop in parallel.

The expected quantity of buildings in the future plays an important role for the needed biobased resources and land in this study's scenarios. The historical time series of built area entails that the future trends follow historical, thus a business as usual of quantity of constructed buildings. The building industry is economically cyclical, which likely is how the future will evolve without major change in policies or paradigms; hence the area prognosis can be considered a " in the middle of the road" scenario. The resulting limitations comprise three main aspects: (i) disregarding the population development in Denmark, (ii) the fact that increased affluence in Denmark might lead to greater consumption of buildings i.e., larger buildings for equivalent functions, (iii) conversely, the increased climate and environmental regulation could lead to policies and mindsets aiming for less constructed area, which is necessary to stay within planetary boundary targets.

We do not include consideration of the substitution effects of other uses of the co-products from the wood, straw and grass, as we apply the 'polluter pays' principle. This could result in less land-use for the wood since it has the largest co-product assumptions. On the other hand, the demand comes from the building industry, which is responsible in some way. Advancing the study's insights would entail system considerations of the co-products. Similarly, this study only assessed upfront land-use and CO_2 storage, A1-A3; it would benefit from a full LCA to determine whether this is leading to a burden-shift across the life-cycle stages. Also, the upfront GHG emissions should be assessed to determine whether that is significantly larger for the fast-growing biobased materials, which ultimately can affect the CO_2-equivalent net-capture potential. Additionally, timing the stored CO_2 in the crops with the regrowth of crops and the release would probably have larger benefits due to the short rotation, previously found to be influential for timber production (Hansen et al., 2024).

Expanding the scope of midpoint impact categories relevant to wood and crops would plausibly follow. In light of this, an assessment of the impact of terrestrial biodiversity from connected midpoint categories such as eutrophication, ecotoxicity, climate change and acidification would be valuable to investigate. That appears imperative, as we have transgressed the biosphere integrity planetary boundary (Richardson et al., 2023).

6. Conclusion

This study first aimed to create wooden building element archetypes for single-family houses (SFH), multifamily houses (MFH) and office buildings (OB) using more straw, hemp and grass materials as substitutes for non-loadbearing wood, finishing and insulation. Second, the study aimed to assess land-use and the stored biogenic carbon of wooden buildings with and without the fast-growing biobased materials for Danish building stock towards 2050, given market penetration rates of 11 % (current), 25 %, 50 % and 100 %.

The trajectory of the demand for materials showed cyclical peaks in 2030, 2044 and 2050. The straw scenarios caused the largest such demand, followed by the grass, hemp and wood scenarios. Fast-growing biobased materials appeared promising for SFH and MFH, with the least potential for OB, and altogether they had the greatest cumulative biogenic CO_2 storage by a factor 1.4–1.9 compared to wooden buildings. Their 50–61 % mitigation of the requirements of wooded land clearly also support their relevance. Nonetheless, Danish land alone cannot fully meet the timber demand in any scenario. The national supply of straw available for construction can cover almost a 50 % market penetration, while Danish production can supply even a 100 % market implementation for the combined straw and grass scenario. The research revealed a reduced land use CO_2 storage indicator, especially for straw. Evidently, this indicator decreases by 4.5 to 10 times for SFH dependent on the scenario, while MFH declines by 3–5 times, and OB by less than a factor of two.

Taken together, the results suggest that using fast-growing biobased materials in wooden buildings is a viable strategy to reduce the requirement for land and to increase CO_2 storage in the production stages (A1-A3). This finding is particularly relevant for Denmark, as it indicates that more building materials can be sourced locally. It also sheds new light on the environmental potential of fast-growing biobased materials in construction, which can assist builders, planners and policymakers in their decision-making. It also lays the groundwork for further research on the environmental assessment and biodiversity benefits.

The limitations of the research converge on using a sample of a single case building for each typology, as this does not represent the entire building stock. The study focuses only on the land and CO_2 storage required for a cradle-to-gate LCA, without examining burden shifts across life-cycle stages and other environmental impacts, and the A1-A3 GHG emissions, which can influence the net capture of CO_2. It also omits the system modelling of co-product substitution in timber production. This can affect the land-use benefits in an improving or decreasing trajectory depending on identified avoided production.

Based on the limitations, more case studies would be of benefit. Further modelling work is needed for an LCA with additional impact categories, e.g., biodiversity. Exploring a consequential LCA to assess how the suppliers respond to increased demand would also be useful. Additionally, expanding these LCA studies to cover building renovation would be desirable. As the culmination of this, investigating the synergies between agriculture and the building sector could provide insights into the environmentally and socially wholesome governance of land.

Despite the limitations and the need for further research, this article suggests that building designers and planners should prioritize incorporating fast-growing biobased materials in wooden buildings to replace non-loadbearing products. Essentially, this helps reduce the obvious trade-off between land-use and climate change regarding timber buildings. The challenge now lies in engineering building elements with appropriate moisture and fire-safety properties. These findings recommend three policy actions: (1) adapt building codes to foster increased implementation; (2) consider national land-use in Denmark to maximize the cross-sectoral benefits of straw and grass production; and (3) provide financial support and incentives for pre-approved solutions conforming to the (adapted) regulation.

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Declaration of generative AI in scientific writing

During the preparation of this work, the authors used Grammarly in order to spell-check the writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Rasmus Nøddegaard Hansen: Visualization, Writing – original draft, Investigation, Methodology, Formal analysis, Conceptualization. **Endrit Hoxha:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Harpa Birgisdóttir:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Francesco Pittau:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors of this paper declare no known competing interest concerning the research conducted in relation to this article.

Data availability

I have shared data as a supplementary file.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107926.

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