Sustainable Cities and Society 70 (2021) 102929

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Land availability in Europe for a radical shift toward bio-based construction

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ARTICLE INFO

Keywords:
Land use
Bio-based materials
Carbon storage
Material-land nexus
Building renovation
MFA

ABSTRACT

The renovation and construction of buildings presents an opportunity for climate change mitigation in urban environments. Bio-based construction is particularly promising since the plant's sequestered carbon offsets the building's carbon emissions. However, the required land to cultivate suitable biomass and the feasibility of environmentally sustainable materials for resilient cities should be understood. This study analyzes timber, straw, hemp and cork construction and renovation in Europe. A prediction-based model, tuned-up on four systems (built environment, natural environment, carbon balance, industrial processing), converts construction activities until 2050 into required material, embodied land and carbon storage. A novel material-land nexus concept analyzes the required land for bio-based construction. Land transformation is not analyzed. The aim is to evaluate the biomass supply considering the current cross-sectoral use of land in Europe. The results indicate that current forests and wheat plantations are more than sufficient for supplying construction materials. Straw seems better than timber, in terms of resource availability and carbon storage potential. Cork is only favorable locally in southern dry countries. The current legal limitations hinder hemp's potential at a large scale. A wider application of bio-based materials remains unrealistic until an appropriate legal framework is provided.

1. Introduction

The United Nations call climate change the defining issue of our time (UN Secretary General, 2018).

The building sector was identified to be a key sector for climate change mitigation (Intergovernmental Panel on Climate, & Change, 2014). Actually, in the European Union (EU) buildings consume 40 % of final energy and cause 36 % of the fossil carbon emissions (European Commission, 2018). Current EU legislation requires all new buildings to be nearly-zero energy buildings (nZEB) by 2020 (European Parliament & the Council of the European Union, 2010) and the revised Energy Performance of Buildings Directive (EPBD) demands a decarbonization of the national building stocks by 2050 (European Parliament & Council, 2018). It has not been quantified yet what exactly this means, but there is a clear potential to reduce energy consumption and carbon dioxide (CO_2) emissions of space heating and cooling since the impacts arising from the operational energy use of a building usually play the biggest role (Heeren et al., 2015). Through renovation the thermal performance of the building envelope can be improved and therefore operational energy reduced. However, studies have also shown that the emissions arising from the production and installation of elements in the building system, which are usually referred to as embodied impacts, can account from 10 % to up to 80 % of the total emissions over the building's lifecycle (Röck et al., 2020). The production of common construction and thermal insulation materials is intense in fossil fuel consumption (Tettey, Dodoo, & Gustavsson, 2014). This suggest that the choice of material is important and the risk of locking into high emission pathways should be reduced by promoting energy efficiency policies and instituting strategies that consider embodied impacts of materials (Reyna & Chester, 2015). Ürge-Vorsatz et al. (2018) stated that the use of low-carbon bio-based construction materials is a key strategy for climate mitigation (Churkina et al., 2020). Bio-based materials offer

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Abbreviations: CO_2, Carbon dioxide; EPBD, Energy Performance of Buildings Directive; EPS, expanded polystyrene; eq., equivalents; ETICS, exterior thermal insulation composite system; GHG, greenhouse gas; GWP, global warming potential; HEM, hempcrete insulation; ICB -, insulation cork board; LC, life cycle; LCA, life cycle assessment; MFA, material flow analysis; nZEB, nearly-zero energy building; OSSB, oriented straw strand board; STR, straw insulation; TIM, wood fiber insulation; TR, technological readiness level.

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https://doi.org/10.1016/j.scs.2021.102929
Received 18 January 2021; Received in revised form 4 April 2021; Accepted 8 April 2021
Available online 16 April 2021
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various benefits: they are renewable, often locally available and during the plant's growth carbon is sequestered (Breton et al., 2018). When bio-based construction materials are used as structural components, their lifespan is usually defined by the building's service life, which easily reaches 100 years (Mequignon, Adolphe, Thellier, & Ait Haddou, 2013). During this time, the carbon is stored in the building. Gustavsson et al. (2017) highlighted the potential of biomass to substitute energy intensive materials such as concrete and steel and Pittau, Lumia, Heeren, Iannaccone, and Habert (2019)) showed that even carbon-negative solutions are possible with bio-based construction. However, using bio-based construction materials for the renovation of building stocks would encompass significant land use for the growth of the required biomass. The potential land requirements need to be investigated for an improved understanding of the feasibility of large-scale bio-based building stock renovation, as well as to analyze how implementing such strategy could disturb land use competition between sectors.

2. Literature review

2.1. Recent developments in bio-based construction technologies

Generally, the carbon cycle of bio-based products is considered neutral since the carbon that is stored in the product is released back to the atmosphere as CO_2 at the product's end of life (ISO, 2012). Using this assumption, different authors could already confirm that bio-based construction materials contribute to a minor GHG emission share over their life cycle when compared to mineral materials (Hill, Norton, & Dibdiakova, 2018; Sandanayake, Lokuge, Zhang, Setunge, & Thushar, 2018). However, it has been recently argued that time influence of carbon storage shoud been considered for biobased materials, between the moment they are incorporated in technical systems and the moment when they are burnt and the carbon released back to atmosphere as CO_2. (Brandão et al., 2013). Accounting for the temporal profile of emissions allowed showing that especially construction material made with biomass from fast-growing plants, is beneficial for climate change mitigation thanks to the fast rotation period of biomass source as was shown by Pittau, Krause, Lumia, and Habert (2018)). The authors found that the fast-growing materials straw and hemp make carbon-negative construction a possibility, while timber construction is less efficient in terms of carbon storage due to the long rotation period oftree plantations. The same authors (Francesco Pittau et al., 2019) conducted another study of the renovation of Europe's building stock and found that fast-growing biogenic materials offer a promising strategy towards reaching the climatic goals of the Paris agreement (UNFCCC, 2015).

2.2. Land requirement for bio-based materials

Bio-based construction materials do not only vary in their structural and thermal properties but also in processing and, importantly, in the availability of raw material. Their manufacturing is dependent on agricultural or forest management, and questions related to land use and land competition between sectors lead to critical issues that need to be investigated.

It was found that land use is an inherent perspective when studying building stocks (Göswein, Silvestre, Habert, & Freire, 2019), since infrastructure and buildings seal the soil (Plutzar et al., 2016) and the production of construction materials need land as an input and in some cases can lead to the degradation of land, e.g. due to the quarrying of gravel (Costea, 2018). According to FOREST EUROPE (2015), from 1990 to 2010, the forest stock, limited to plantations of coniferous trees, grew across the EU member states. This net change of the growing stock could be removed while keeping plantation stands constant. Yet, a natural limitation of available resources imposes land use competition between interest groups for wood and other bio-based materials (Manuschevich, Sarricolea, & Galleguillos, 2019) and can cause conflicts between sectors (Bonsu, Dhubháin, & O'Connor, 2019). In other places, reforestation efforts to sequester carbon should not be counterfeit through logging, as was emphasized for Vietnam (Scheidel & Work, 2018). While the global European forest area is growing and the agricultural land is shrinking, the exact opposite can be observed on a global level, according to Smith et al. (2010). Globally, increased wealth is followed by increased per capita meat consumption. This is relevant for land use because producing meat requires significantly more land than producing crops (Smith et al., 2010). Moreover, the increased meat demand, particularly of the rich Global North, coupled with a decline of agricultural land, leads to an environmental cost shifting to the Global South, where an increasing amount of required food is produced and then exported (Haberl, 2015; Muradian & Martinez-Alier, 2001).

Yields can only be increased by increasing inputs such as land, labor, or fertilizers (Haberl, 2015). Relying on the intensified use of biomass for construction, and in other sectors, can only result in reduced GHG emissions if a sustainable forest management and sustainable agriculture are guaranteed. The former concept refers to a successful biodiversity conservation of species group such as fungi, microhabitats, herbaceous plants, insects and birds (Lindenmayer, Margules, & Botkin, 2000; Zytynska, 2018). The latter concept refers the avoidance of soil, air and water pollution from a physical, biological and chemical point of view (Hobbs, Sayre, & Gupta, 2008). Another important parameter for sustainable intensification of harvest yields is to reduce costs for farmers (Hobbs et al., 2008).

2.3. Modeling the natural systems by adapting the land-material nexus

Land use has been under scientific scrutiny for many years and various articles have researched land competition between sectors, mostly for the production of food and biofuels (Tomei & Helliwell, 2016). Land competition can lead to increasing food prices (Rathmann, Szklo, & Schaeffer, 2010) and a higher demand for arable land, which often substitutes forest or jungles with farmland (Graham-Rowe, 2011). The development of the first generation of biofuels made with cereal and sugar crops, caused a food crisis since crops were reallocated for energy production. Specifically affected were countries of the Global South. For example in Brazil, feedstock plantations are often owned by foreign investors, which caused hunger in some parts of the population while the economic gains of this trade only benefitted few (Gasparatos, Stromberg, & Takeuchi, 2013). These problems are translatable to bio-based construction materials and we need to use the opportunity now to guide policymakers in avoiding similar mistakes made in the past. For example, for biofuels, a demand-side management strategy that regulates user behavior, and improves energy use efficiency, was recommended (Ji & Long, 2016). Other recommendations include the protection of rural communities, commensurate investments in food and nutrition security, and transparent public–private partnerships to avoid burden-shifting to low income communities (Renzaho, Kamara, & Toole, 2017). The food-energy-water nexus concept proposes to analyze these flows as closely intertwined, which helps to uncover dynamics and potential problems (Engström et al., 2017; Hong et al., 2019; Sadegh et al., 2020). Some scholars are pushing towards the use of the nexus concept to also include effects of land use and land use change. A recent review of urban studies is advocating for a nexus framework to analyze nature-based solutions, ecosystem services and urban challenges, which include the built environment (Babí Almenar et al., 2021). Zhao et al. (2018) proposed to model water-land-energy-carbon nexus for an improved understanding of the impacts of land resource exploitation of agricultural production. Börjesson and Gustavsson (2000) integrated the net demand for productive forest area that is needed for the raw material and energy supply for a case study building in Sweden. The authors highlighted the importance of expressing emission reduction potential per area of forestland since usually the forest is a limited resource. We could not find any other previous studies that link land requirement with construction material demand at a transnational scale.

In this paper, we utilize the material-land nexus concept to uncover land use consequences of bio-based material use in the construction sector. The term “embodied land” was coined to calculate amount of land per year required to sustain a product, e.g. a building, in terms of energy and materials (Rovers, 2013) but there are only few studies that link the material requirement for a building with the required land.

3. Goal and scope

The goal of the present study is to investigate the possibility of using bio-based construction materials at the pan-European level and identify possible barriers for the transition to full bio-based building. The most promising materials from a technical perspective are selected as case studies, i.e. materials that have sufficient structural or thermal insulation properties. The first research question asks which of the selected bio-based materials contributes to the highest carbon storage potential in buildings and the highest carbon efficiency parameter. The latter is a new parameter and expresses kg of CO_2 equivalent per hectare of land needed to grow the raw material. The current potentially available land to source the different biomasses to use in construction is employed as a hypothetical maximum value of present conditions. These values are collected by Country and then summarized by Geocluster. The calculation considers plant growth rates, land requirements for different types of raw materials and inter sector competition. The second research question asks how much the total carbon storage potential of a bio-based European building stock is. The present study does not analyze potential consequences on the ecosystem equilibrium but aims to quantify the potential of the existing European bio-infrastructure to supply biomass for the construction sector. This can help policymakers to introduce a new legal framework and eventually economic incentives for implementing carbon storage in buildings and cities.

4. Method

4.1. MFA modelling

A specific material flow analysis (MFA) model was developed to simulate the material intensity expected in the next years in EU-28, as well as the raw bio-based materials which the natural systems (plantations of trees and crops) need to supply. The model is divided into four main parts: built environment, natural environment, transition, and carbon balance. Fig. 1 gives a schematic overview of the model and the following subsections provide detail on the integrated tools and methods, which are applied to the European building stock for different construction technologies and materials. The built environment model is connected to the natural environment model through the industrial processing model. The carbon balance model is linked individually to the other three models.

The built environment model comprises only the residential building stock and simulates the future construction material requirement according to different construction alternative technologies for new construction and retrofitting. The natural environment model encompasses the raw material demand and its translation to land requirement for biomass regeneration. The industrial processing model estimates the biogenic material intensity based on raw material demand through information on intermediate processing and construction material production. The stock in the industrial processing model is called biogenic material and lies in-between the two processes of the industrial processing model. Finally, the carbon balance model is composed of a carbon emission model and a simplified model to account for carbon uptake from plant growth.

Demolition and re-construction of existing buildings were outside

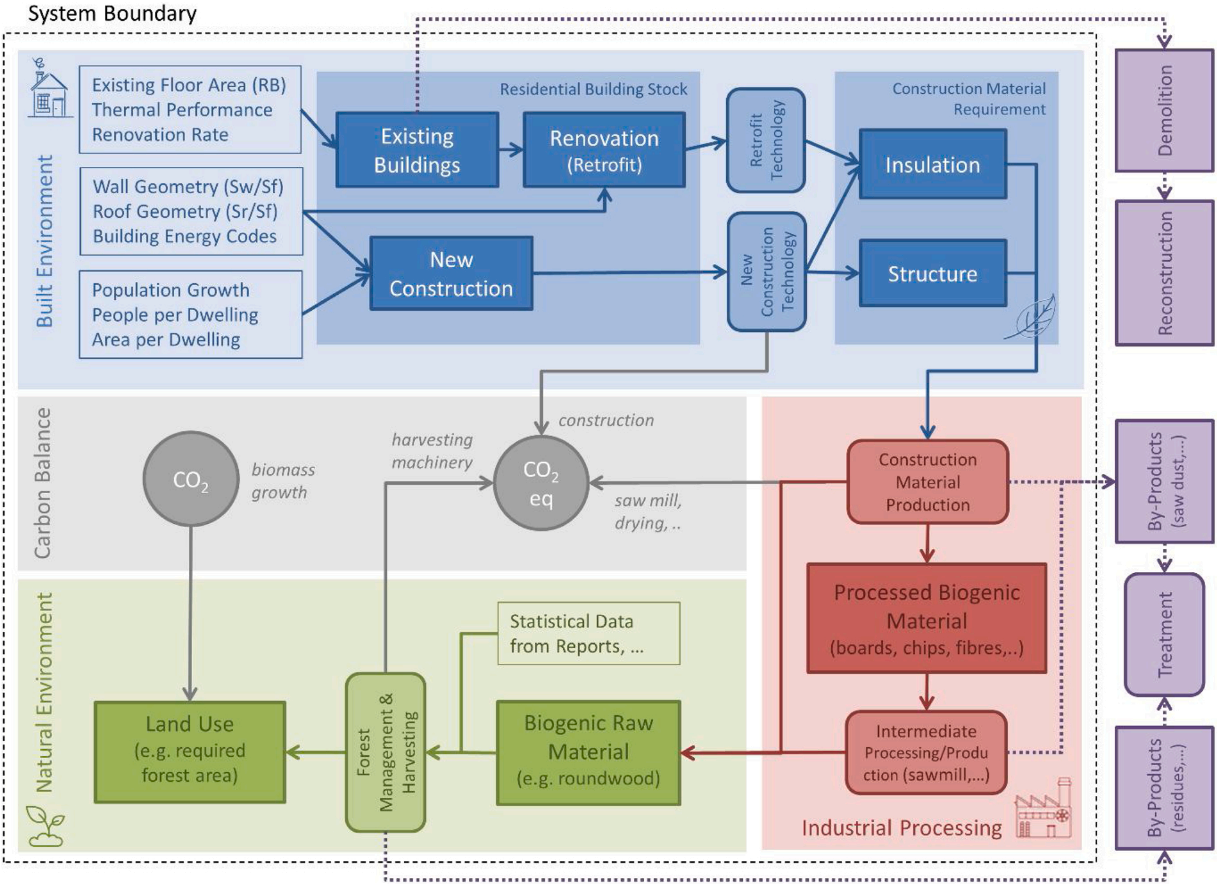

Fig. 1. Schematic overview of the system boundaries and model divided into the four systems Built Environment (blue), Carbon Balance (grey), Natural Environment (green), and Industrial Processing (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the system boundaries, as shown in Fig. 1. Moreover, by-products from forest management and harvesting, intermediate processing and construction material production, and their treatment, were not considered. The model characteristics were based on the recommendations given in the framework for the study of dynamics of building stocks by Göswein et al. (2019) for the research goal "material choice".

The model was applied to the EU-28 member states. The states were sorted into seven geographical clusters according to their climatic conditions as was proposed by Birchall et al. (2014), called "geoclusters" (Sesana et al., 2015). A map and table showing the division of the EU-28 countries into geoclusters can be found in Supplementary Information (SI – Annex A). The analysis was performed from present day until 2050. The model only considers energy-retrofit and new construction of walls and roofs of the residential building stock.

More information on the residential building stock modelling can be found in the SI, Annex A and E.

4.2. Reference construction technologies

Four alternative bio-based construction technologies were considered in the analysis, based on four different insulation materials: wood fiber (TIM), straw (STR), hempcrete (HEM) and cork (ICB). A specific assembly for each alternative was developed, based on the proposition (renovation or new construction), and element (roof or exterior wall). Only the building envelope components above the ground were included into the analysis. Two renovation options were assumed to be fully prefabricated (timber and straw) and two onsite-construction options (hemp and cork). Thus resulting in sixteen slightly different technology options, eight for new construction and eight for renovation. A more detailed description of the different technology options can be found in SI – Annex B and E.

4.3. Material processing

Built environment and natural environment models were connected with an industrial processing model, which takes into account the mass flow changes of bio-based products before and after industrial processes. In a production process, often the material flow, which enters into the system is not equal to the outflow. Especially in bio-based processes, a large amount of biogenic residues can be generated during manufacturing, by lamination, cutting, drilling, planning, etc. The industrial processing model and more information on the biogenic content of the construction materials can be found in SI, Annex E.

4.4. Bio-systems modelling

Fig. 2 shows the available area for the production of different types of biomass in the EU. The biomass with the biggest land cover is wood, followed by cereals. Cork is only available in south-western Europe, while hemp is available in many European countries but underlies certain policy restrictions, therefore remaining limited.

Bio-systems modelling is a complex research field of its own. Especially for plantations of trees modelling, different dynamics should be included in the analysis: the rotation period of trees, tree species, type of soil and the local climate influence the harvest potential (Ramage et al., 2017a) and global warming potential (GWP) due to CO_2 emitted from biomass (Cherubini, Peters, Berntsen, Strømman, & Hertwich, 2011). A simplified approach is to include plantation growth in a model through statistics.

The land required to meet the biogenic raw material demand was calculated by using the yield (kg/ha) per Country for the four biogenic raw materials and dividing the annual biogenic raw material demand by the yield calculated from the current harvest and land use (see SI, Annex C and E). The Country specific values were then averaged per Geocluster. The actual yearly required biomass (dB_{act}), which is based on the building stock model, as described in SI, Annex E is the driver of yearly required land to grow the different types of biomass (dL), which is dependent on biomass density (B_D) and considers a factor for material losses during cultivation (ε) as shown in Eq. (1):

$$dL = dB_{act} \cdot B_D \cdot \varepsilon \tag{1}$$

The following sections provide more information on the production and available share for the construction industry of each type of material. The research on novel bio-based materials for innovative construction systems is a trending topic which involved several scholars in recent years. Many of them investigated the use of unconventional sustainable materials for building insulation. Some of those studies argued about the limitations of a large implementation of plant-based by-products due to the inadequacy on achieving competitive thermal or acoustic performances, e.g. corn cob (Pinto et al., 2011), reed mats (Tsapko, Tsapko, & Bondarenko, 2020), miscanthus and sunflower stalks (Eschenhagen et al., 2019). However, a recent study (Kuittinen, Zernicke, Slabik, & Hafner, 2021) showed that there are plentiful bio-based construction products available with a high technological readiness level (TRL) up to and including TRL 9 "technology used at large scale". Some other studies discussed about the limits of new processes at early stage of the development and their performance reliability under long terms conditions, which may affect the durability, e.g. sunflower cake (Evon et al., 2015), cotton stalks (Binici, Eken, Dolaz, Aksogan, & Kara, 2014), mycelium-based products (Girometta et al., 2019). Consequently, for this work only a short list of local bio-based materials widely available in the European market and already commonly used in building design were selected.

4.4.1. Managed forests

Only coniferous wood (softwood) was considered for this paper since construction materials, especially when used for load-bearing structures (e.g. glulam, CLT, etc.) are largely made of coniferous species, e.g. pine, spruce, larch, etc. (Ramage et al., 2017b). The net annual change of coniferous wood species was estimated according to the following Eq. (2):

$$\frac{dN_{cc}}{dt} = \frac{dN_r}{dt} \times f_{ct} - \frac{df}{dt} \times f_{crr} \tag{2}$$

where:

- dN_{cc}/dt is the coniferous net annual change;
- dN_r/dt is the net annual increment of roundwood;
- f_{ct} is the share of coniferous trees standing in the EU plantations;
- df/dt is the annual felling;
- f_{crr} is the share of coniferous roundwood removals

To estimate the area that corresponds to the coniferous net annual change, the following Eq. (3) was considered:

$$A_{cc} = A_f \times f_{ct} \times f_{cc} \tag{3}$$

where:

- A_{cc} is the area available for the coniferous net annual change;
- A_f is the total EU plantation of trees area available for wood supply;
- f_{ct} is the share of coniferous trees;
- f_{cc} share of the coniferous net annual change.

According to Ramage et al. (2017a,b) mostly coniferous and thus softwood is used for construction. Therefore, this study only considered coniferous roundwood, making up about two-thirds of the total roundwood available for wood supply. It should be noted that a considerable additional potential could be found in non-coniferous wood. In 2010, 162 Mm^3 out of the total 338 Mm^3 of industrial roundwood, were available for the manufacturing of construction products (Eurostat, 2015).

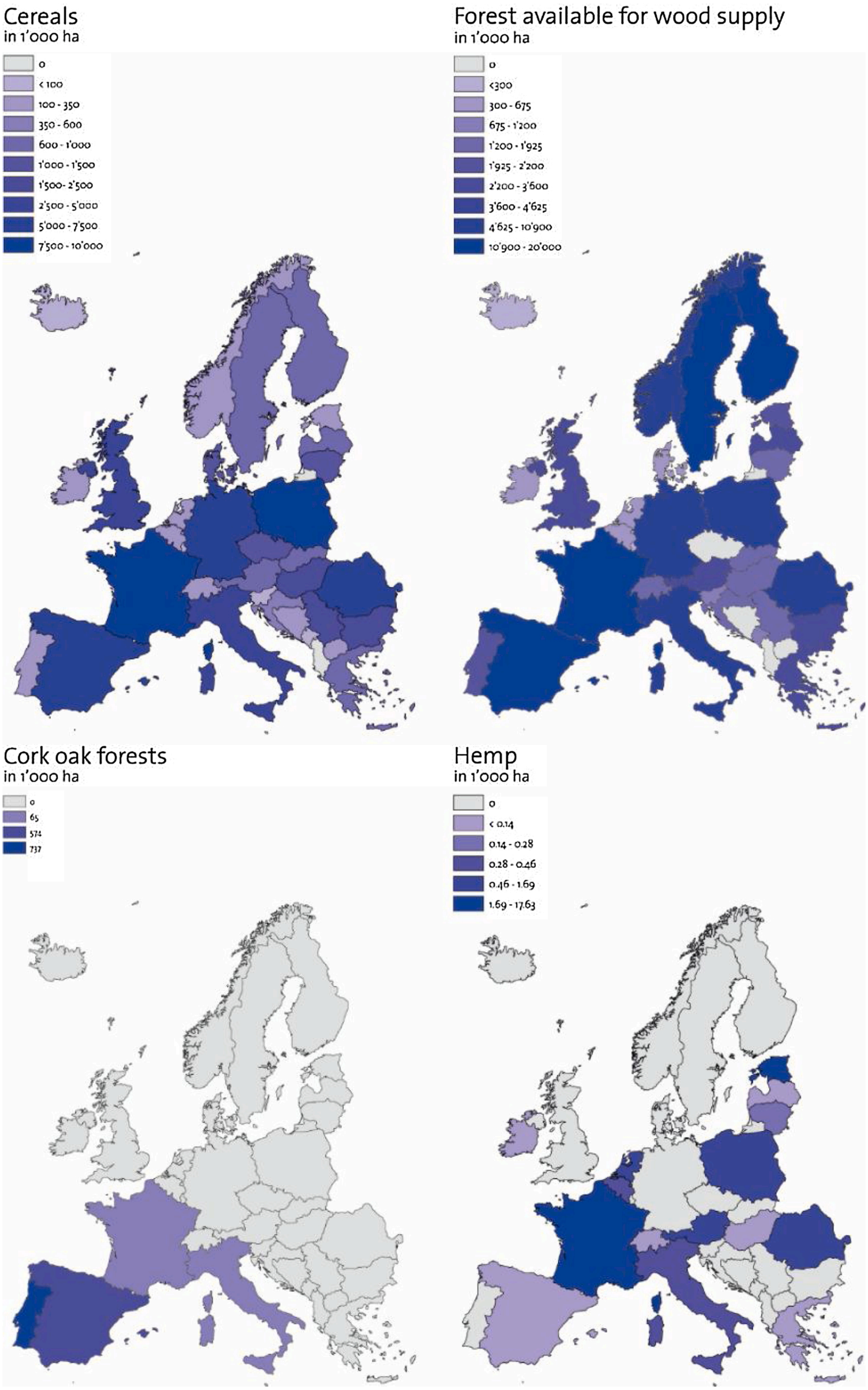

Fig. 2. Existing land for the cultivation, harvest and production of different types of biomass in Europe. Sources: Cereals (Eurostat, 2017), Forest (Eurostat, 2015), Cork oak forests (APCOR, 2013), Hemp (Eurostat, 2017).

4.4.2. Straw from cereal cultivations

Cereal production statistics area used for cultivation of cereals were derived from EuroStat (Eurostat, 2017). The amount of cereal produced each year was translated into amount of straw, through the straw-to-corn ratio, which is 0.848 based on Hartmann, Kaltschmitt, and Thrän (2016). A German study (Münch, 2008) compared different recommendations and came to the conclusion, that on average one third of the straw can be taken out of the agricultural cycle/system and is hence available for all types of applications. Currently most of the straw is left on the field after the harvest to provide nutrients for soil regeneration or used as animal bedding and feed. Other secondary usages of straw are in horticulture and gardening and for energy production, which account for 1% of the current EU-28 straw production (Hartmann, Kaltschmitt, & Thrän, 2016).

4.4.3. Shives from hemp crops

Eurostat data for hemp production was used (Eurostat, 2016). The hemp production was multiplied by a hemp straw to hemp shives ratio suggested by Zampori, Dotelli, and Vernelli (2013)). A share of 16 % of hemp shive production was assumed to be available for construction based on the years 2010 and 2013 as suggested by Carus and Sarmento (2016a),b). Uses in other sectors are not necessarily dependent on hemp shives and alternative raw materials could be used. This is because hemp shives are still considered a waste product, meaning it is be realistic to allocate the entire production of hemp shives to the construction sector.

4.4.4. Cork from oak plantations

The model considers that to harvest the bark of cork oaks, which grow in large cork savannahs mainly in the western Mediterranean Basin, specific harvest cycles need to be followed (Gil, 2015). The regional share of cork production was derived from Aronson, Pereira, and Pausas (2009)) and multiplied with the annual cork production for the EU stated by Bugalho, Caldeira, Pereira, Aronson, and Pausas (2011)). A reference rotation period for the regeneration of the bark was assumed equal to 9 years (Demertzi, Paulo, Faias, Arroja, & Dias, 2017). Currently 72 % of produced cork is used in the wine industry, followed by the construction sector, with 25 % where cork is used to manufacture products for floors, thermal insulation and coverings (APCOR, 2019).

4.5. Assessment of carbon emissions

Climate change is caused by anthropogenic activities leading to increased greenhouse gas (GHG) emissions into the atmosphere (Cook et al., 2016). The main GHG are H_2O, CO_2, CH_4, and N_2O. For construction products, carbon dioxide (CO_2) and methane (CH_4) are the major contributors to overall GHG emissions.

The GWP for 100 years was calculated with the impact assessment (LCIA) method IPCC 2013 Version 1.03 (Krug, 2013). This method considers all relevant GHG emissions according to the IPCC and converts them into CO_2 equivalents (eq.) (IPCC, 2001). For example, the GWP of 1 kg of fossil CH_4 over 100 years is equal to 28 kg of CO_2 eq (Kaito et al., 2014). The GWP compares the integrated radiative forcing over 100 years from a unit mass pulse emission relative to CO_2 (IPCC, 2007). The present paper analyzes the GWP arising from the production and construction life cycle (LC) stages A1 to A5. The LCA follows EN 15804 (EN 15804, 2011). The functional unit is 1 m^2 of constructed area (roof or external wall) with a defined U-value, which is depending on the geocluster.

4.6. Carbon uptake from biomass regrowth

Plants sequester carbon during their growth. The amount of sequestered carbon per type of material was multiplied with the total amount of biomass demanded by the construction activities of the EU. We assumed a sustainable supply of biomass, meaning all biomass used in construction will be regenerated in nature. In this way, the carbon storage potential of buildings was calculated and actually refers to the cumulative carbon uptake from biomass regrowth. The carbon coefficients (kg of carbon per kg of biomass) of hemp, straw, cork, and timber can be found in SI – Annex C.1. Since the impact category GWP is expressed in kg of CO_2 eq., the carbon storage also needs to be translated into CO_2: 1 kg of carbon equals 3.67 kg of CO_2, considering the atomic weight of the molecules (Hoxha et al., 2020).

5. Results

The results are divided into three sections. The first sections presents the material requirements of the demand-driven building stock model, which form the basis for any further analysis of land use and carbon storage. The second part answers the first research question which bio-based materials are most promising considering present conditions. The third section answers the second research question regarding the carbon storage potential of a bio-based European building stock, expressed in carbon efficiency (kg of CO_2 eq. per ha of land).

5.1. Material Intensity from renovation and new construction

As a first step, the envelope area of the buildings, divided into new construction and renovation was estimated for the EU-28. The cumulative expected new construction in 2025 accounts for to 0.29, and reaches 1.51 Million (Mio) m^2 in 2050 (Fig. 3 left). Most of the geoclusters' construction activity can be expected to slow down over time mostly due to a gradual stabilization of construction activity by 2050 of Mediterranean and northern continental geocluster. However, southern dry and oceanic countries showed a slightly constant increase of new construction activity. In comparison, building renovation, as shown in Fig. 3 (right), is expected to keep a constant rate based on the beforementioned assumption, amounting to 7.84 Mio m^2 renovated envelope area by 2050.

The envelope area was combined with the different technologies, as summarized in Table 2 of SI, Annex E, to estimate the amount of required material, as shown in Fig. 3, both for renovation and new construction.

Considering the renovation alternatives, the continental geocluster always requires the highest share, accounting for almost half of the material intensity, independent of the renovation technology. Southern continental countries are the second most construction material intense, followed by the Mediterranean countries, while oceanic, northern continental and nordic continental geoclusters accounted for the lowest material intensity. Particularly, Spain and Portugal from southern dry geocluster indicate even lower numbers and are barely featured in Fig. 4.

The results for new construction however, showed that the geocluster with the highest material intensity is the oceanic. Mediterranean, southern dry and Nordic countries account for material intensities of about equal amounts, while material requirements in the continental geocluster are comparably low. Finally, the material intensities of the northern continental, and southern dry geocluster, are insignificant.

Fig. 5 shows the average yearly material intensity grouped for each technology alternative by component. The material intensities for the four renovation technology options are higher than those for new construction, due to a comparably larger amount of envelope area being renovated than new required. The hemp-based technology option is the most material intensive in for renovation and for new construction. The straw-based technology option requires the second largest amount of construction material, closely followed by the cork-based technology option. The timber-based technology option is the least material intense, while the straw-based retrofit option requires a high structural mass, due to the light clay – straw mix, which was considered as a structural material instead of an insulation material. The differences in structural mass less are prevailing for new construction. As for insulation material, the hemp options require the highest mass to fulfill the thermal insulation requirements. The cork-based retrofit option is the only that does

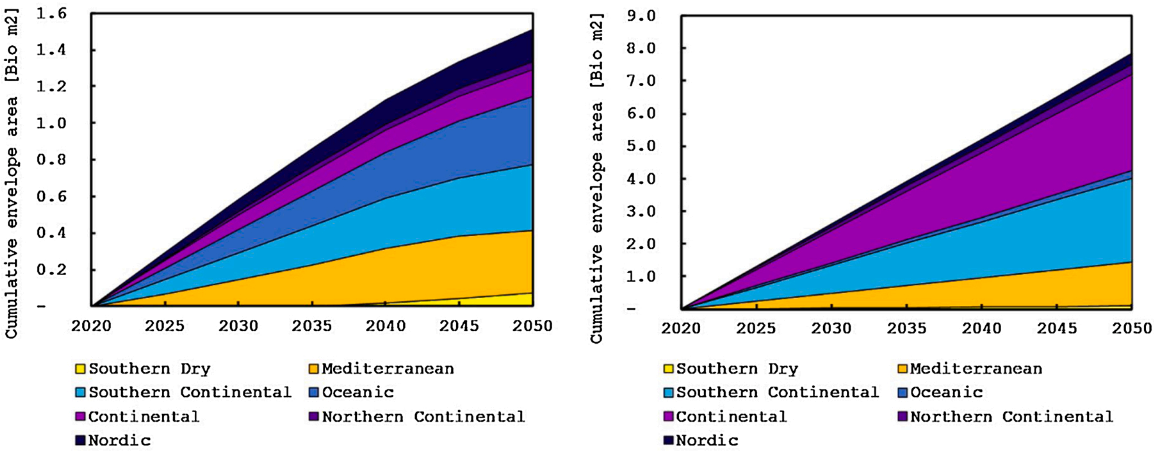

Fig. 3. Cumulative area of renovated exterior building façades for EU-28 countries over time in billion (bio) m^2 per Geocluster. On the left for new construction and on the right for renovation. Elaborated data from ODYSSEE database (ENERDATA, 2018).

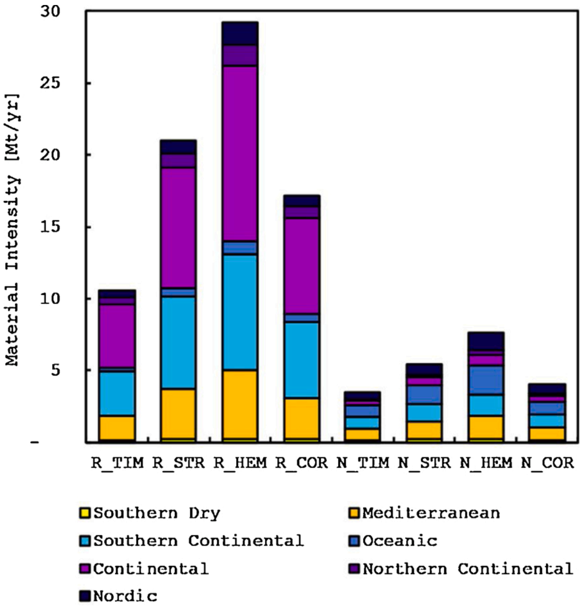

Fig. 4. Yearly material intensity for renovation and new construction estimated as mean value for the period 2020-2050. Shown are the summed up material requirements for exterior walls and roofs. The coding on the x-axis refers to technology options as described in Table 2 of SI, Annex E. "R" states for renovation, and "N" is for new construction.

not require any structural frame: the ICB can be directly applied to the existing structure.

5.2. Land availability for biogenic raw materials

Fig. 6 shows the supply and demand of biomass for the four studied materials, considering the row material ideally available for construction sector. Each of the geoclusters could only supply enough straw (top left) and roundwood (top right) to fulfill the regional demand. All the 28 EU member states have significantly higher straw supply, than straw demand for construction activities. The supply of cork is only sufficient to meet the full construction-induced demand in the Southern dry geocluster (bottom left), that is 268 ktons per year compared to 21 ktons per year needed for construction. Cork could supply 7.2 % of the demand when considering total available cork and even less, 2.2 %, when only the share available for construction is considered. This result is valid even though cork is produced in four countries, situated in three different geoclusters. Hemp (shown in Fig. 6 bottom right) is cultivated in six out of seven geoclusters. Current hemp production could only cover up to 2.3 % of the modelled EU's construction activities. None of the geoclusters, and internally none of the member states, can satisfy their hemp shives demand with their current production. The largest supply of hemp is produced in the Southern Continental geocluster, with an annual production of 97 tons. The roundwood supply refers to the amount that can be taken from plantations without harming the regeneration capacity of certified from sustainable forests management. However, in many regions where forestry is not a dominant sector for economy development, the forest management is mostly inefficient. Consequently, wood extraction is not optimized and often mature trees are not clear-cut, with a high risk of wild fire and trees mortality.

5.3. Land use and carbon storage potential

The cumulative mass of CO_2 that can be potentially stored in wood and bio-based construction products by 2050 was estimated for the four alternative construction solutions in EU-28, as well as the corresponding land required to grow the biomass and fulfil the annual demand of biobased construction materials.

Fig. 7 shows the land available and required to supply the annual material demand. As shown in the graph, the land available to supply wood and straw is more than sufficient to fulfill the full demand from construction. In particular, the land needed to supply roundwood for timber, sawn wood and insulation is 23 % of the total land available for construction, meaning that neither land pressure nor cross-sector competition is expected if the TIM construction alternatives are largely used to fully supply the construction demand. Similarly, straw is largely available in Europe, and the construction sector requires only 12 % of the land today available for construction if STR construction alternatives are used. Contrary, the current land to supply both hemp and cork insulation in HEM and ICB solutions are far to be sufficient to fully supply the material demand. Namely, in case of HEM only 1% of the land needed for material supply is available for construction, while for ICB the available land for oak savannas covers 2.2 % of the land demand.

The total cumulative mass of CO_2 that can be stored in construction products by 2050 is shown in Fig. 8. In case of TIM, STR and HEM, roughly the same amount of CO_2, between 602 and 616 $MtCO_2$, can be ideally stored, while a slightly lower value is expected for ICB, 386 $MtCO_2$, due to the higher thermal proprieties of cork insulation, which, compared to alternative insulations, requires less material to reach the same U-value. Contrary to TIM and STR, the cumulative mass of CO_2 ideally stored in HEM and ICB is strongly limited by the availability of land for growing the resources, since only 2% and 4% respectively of

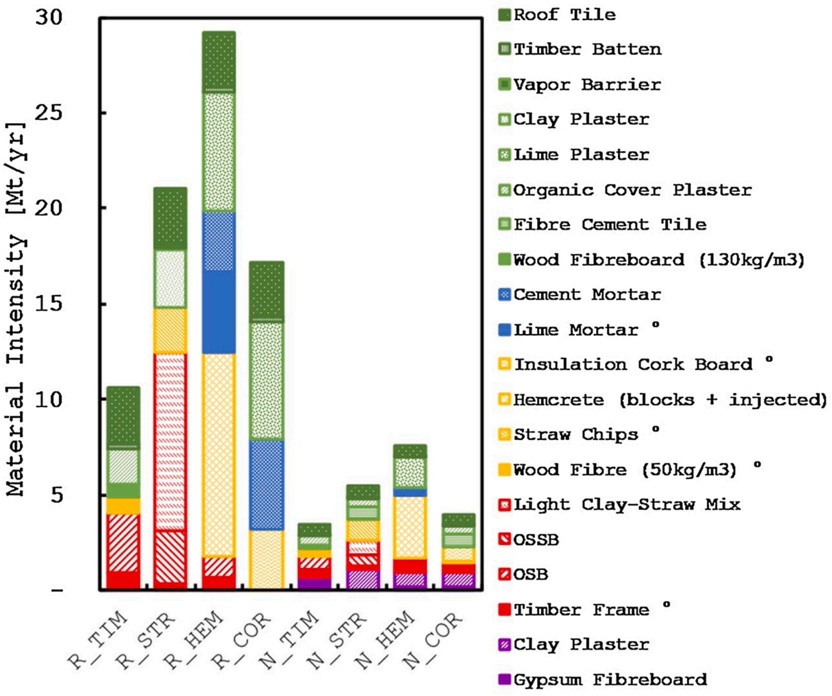

Fig. 5. Yearly material intensity for renovation and new construction, evaluated as mean value for the period 2020-2050, for exterior walls and roofs, for the eight technology options per type of material. The materials are color-coded depending on the functions of the main components: purple = interior finishing, red = structure, yellow = insulation, blue = adhesive, green = exterior finishing. “R” states for renovation, and “N” is for new construction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

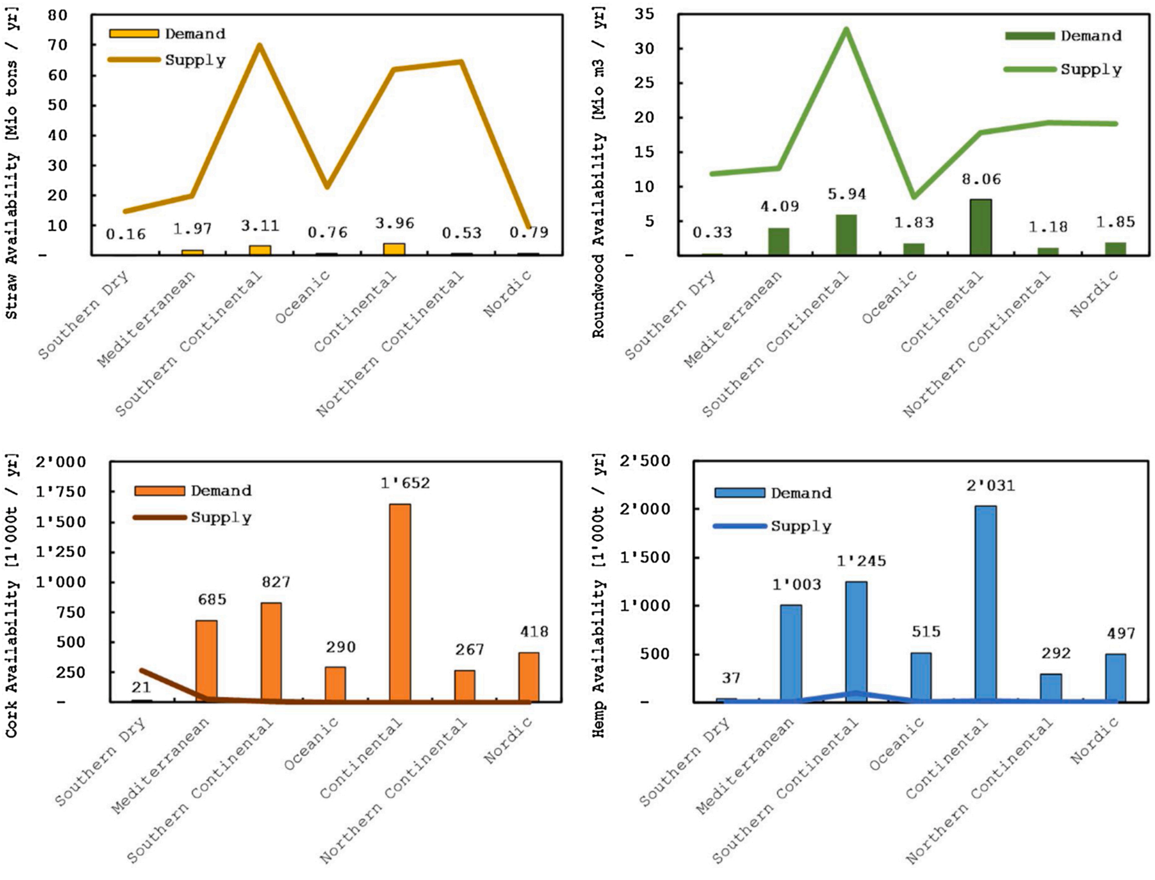

Fig. 6. Net-available annual biomass for the different types of bio-based materials, calculated as mean value for the period 2020-2050. Top left: straw, top right: round wood, bottom left: cork, bottom right: hemp.

bio-based material can be supplied for construction, limiting the possibility to effectively store the carbon in construction products.

Finally, the land efficiency coefficient for each alternative construction solution was evaluated, which estimates the extension of land required to store 1 tCO_2 in the built environment. As shown in Fig. 9, compared to STR, TIM requires less land to store the same amount

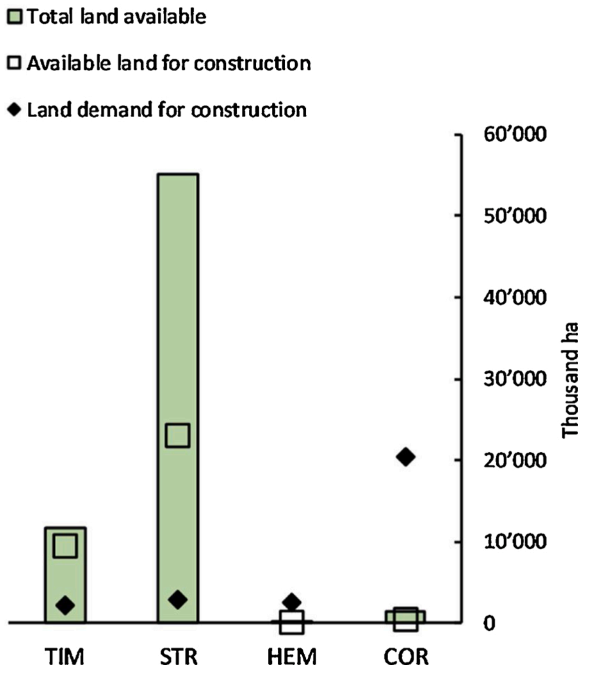

Fig. 7. Land requirement and land availability in Europe to supply the annual demand of biogenic resources for the four alternative construction solutions under study.

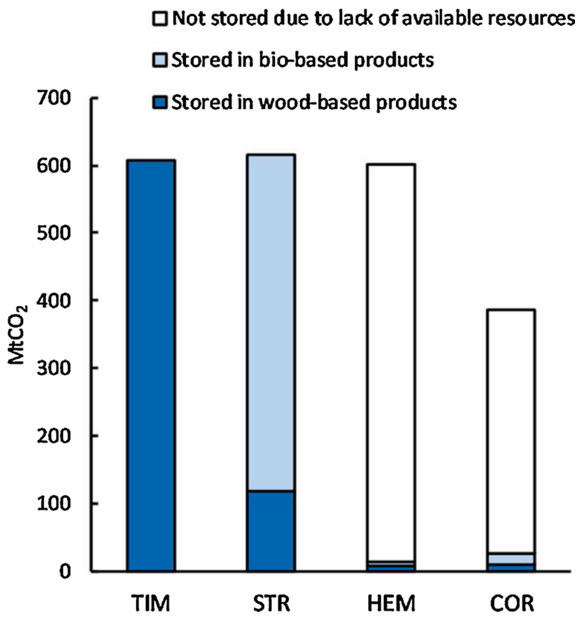

Fig. 8. Cumulative carbon storage potential for the four alternative construction solutions under study by 2050.

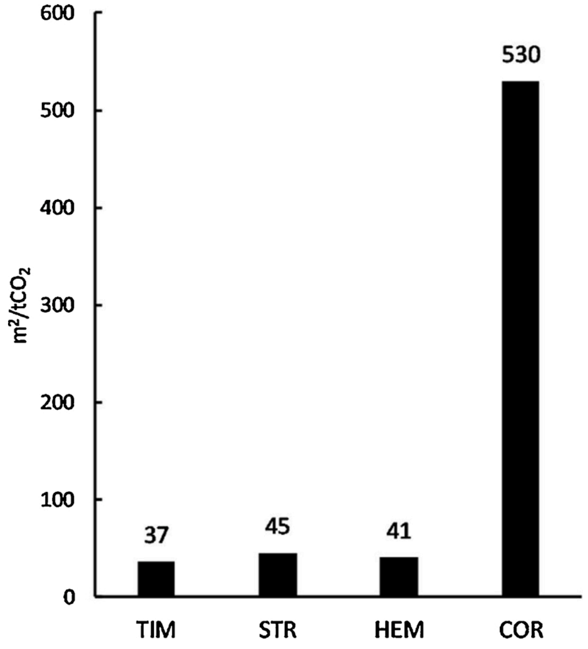

Fig. 9. land efficiency coefficient for the four alternative construction solutions under study, which estimate the extension of land (in m^2) required to store 1 tCO2 in the building stock.

of CO_2 in buildings, due to both a higher yield and a higher carbon content in forest products. Moreover, as shown in the previous graphs, both materials are commonly available all over Europe and locally available in every country, contrarily to HEM that, even if shows a low land efficiency coefficient, its availability in each Geocluster is minimal. The ICB solution, even if potentially able to supply the full demand of Southern dry Countries, namely Portugal and Spain, is far to fulfill the whole European demand. Moreover, Cork is much more inefficient compared to alternative biobased materials, and the reason are: i) low tree density in the savannahs; ii) low volumetric mass in final product (i. e. expanded cork insulation), and iii) low yield in plantations, since only the bark is harvested from the oak tree. This is reflected on the space efficiency, which results as ten-folds higher than the other three alternative solutions.

6. Discussion

6.1. Sustainability considerations of intensified harvesting

Forests, intended as plantations of trees, provide a series of both tangible and intangible services to society and to human well-being, ranging from the production of raw materials and regulation of water flows to the protection of soils and conservation of biodiversity. In the countries that form the EU, forests account for approximately 38 % of the total land surface, out of which more than 95 % are managed with practices that vary broadly across countries (Duncker et al., 2012; Schelhaas et al., 2018). Emerging wood markets driven by the bio-economy are challenging the current balance between wood demand and the need to preserve key ecosystem services. In particular, in recent decades forests are increasingly considered to be a key asset for meeting climate mitigation targets (Grassi et al., 2017).

However, a recent study showed that the intensity in harvest suddenly increased after 2015 (Ceccherini et al., 2020), with particular contributions from large EU domains such as the regions of Finland, Sweden, Lithuania, Latvia, Estonia and Poland, and the western part of the Iberian Peninsula. Econometric studies confirmed that the increase in the rate of forest-products harvest is the result of the recent expansion of wood markets (Ceccherini et al., 2020). It is clear that if such a high rate of forest harvest continues, the post-2020 EU vision of forest-based climate mitigation may be hampered, and the additional carbon losses from forests would require extra emission reductions in other sectors in order to reach climate neutrality by 2050.

These recent results are a strong argument in favour of fast-growing bio-based materials for insulation. In particular, materials that are currently by-products of agricultural practice. Wheat straw seems to be the safest option to promote as an alternative building material. Wheat is already produced everywhere in Europe, so no change of land use would be induced. Even when considering that a third of total produced straw is needed back on the field to close nutriment loops, we have shown that the demand for construction is negligible compared to the availability of straw in Europe.

This result might be different for hemp where a change of land use would be required. Studies show that compared to other energy crops, industrial hemp has the potential to become a promising feedstock for generating biofuels and value-added products that can potentially provide a boost to the bio-economy (Das et al., 2020) and hemp for construction would be a by-product of such bio fuel economy. For example, in the North East of France, the locally established value chain of cultivating sugar beets for the production of sugar deteriorated drastically in the 80's, which pushes farmers to switch to growing hemp. This opened a new economic horizon (Lewis, 1987). However, this business model might not be transferable to all of Europe. Additionally, hemp can be used for phytoremediation of degraded land, particularly for cadmium-contaminated soil. In such circumstances, hemp could be used to regenerate brown fields, while avoiding land competition with existing crops (Cundy et al., 2016).

The use of wood, although a tempting possibility, as the construction timber sector is already well structured and in expansion in all European countries, raises the risk of land competition and cascading effects through indirect land use changes, a phenomena which, for example, already negatively affects the environmental impacts of biofuel production (Lambin & Meyfroidt, 2011). Biodiversity plays a fundamental role in forest since it allows to resist to parasite attacks, violent storms and even wildfires, as shown by several authors (Cowling, 1978; Thompson, Mackey, McNulty, & Mosseler, 2009; Thompson, 2011). The plantation of trees, on the contrary, is an artificial system that requires heavy investment to be realized. The origin, distribution area and rotation are governed by the economic operators according to the market needs. In artificial plantations of trees the diversity of plants is low by definition and the diversity of animals is low due to the lack of food resources for wildlife. Brockerhoff et al. (Brockerhoff, Jactel, Parrotta, Quine, & Sayer, 2008) argue that plantations can make an important contribution to biodiversity but only where they replace human-modified ecosystems (e.g. degraded pasture) and not where they replace native ecosystems. Intensified use of non-monoculture forests would certainly affect the biodiversity and cause trade-offs with other ecosystem services of the forest, e.g. water provisioning, soil fertility, and recreational purposes (Haberl et al., 2014; Smith et al., 2010). For this reason, this paper investigates only the effect from a supply side of intensified harvesting of wood from artificial plantations of trees. Another concern relates to the fact that intensive harvesting of forests, where even logging residues are harvested, could lead to a decrease of soil organic carbon (Achat, Fortin, Landmann, Ringeval, & Augusto, 2015). Quantifying these aspects are beyond the scope of this paper but should be considered in future consequential LCA studies (Ritter, De Rosa, Falk, Christensen, & Løkke, 2013). Land competition has positive and negative consequences, for example increased efficiency usually comes with increased use of non-renewable resources such as water and fertilizer (Haberl, 2015).

6.2. Timber and straw are most promising

The results of the present study showed that the widespread materials timber and straw have the highest potential of storing carbon in the European building stock.

Using straw as a construction material offers various benefits. Firstly, wheat straw is an agricultural by-product of wheat production. Wheat straw is not used as industrial raw material except for a minor portion that is reserved as animal feed, household fuel, or as raw materials for paper industry (Sun, She, Sun, & Jones, 2010). Moreover, wheat production is actually growing in the EU-28, therefore the amount of straw available is increasing (Eurostat, 2019). Secondly, straw, compared to timber, has the advantage that it is sourced from a fast-growing plant with a rotation period of one year or less. A recent prominent research showed that planting an additional 0.9 billion hectares of tree canopy cover, would be a climate change solution (Bastin et al., 2019). However, forests might grow too slow to be able to mitigate climate change impacts with regard to the timeline of the Paris climate agreement and its target year 2050 (UNFCCC, 2015), considering that many tree species take decades to fully grow (Pretzsch, Biber, Schütze, Uhl, & Rötzer, 2014). This issue is not dealt with in the present study since it assumes that carbon storage is equal to carbon uptake, which is only correct for fast-growing biomass such as straw, but not for timber if the time horizon considered, in this case 2050, is shorter than the rotation period of the forest. In addition, there are the questions of land use competition and ecosystem services. For instant, wood used as timber has many other applications, e.g. paper, packaging and bio-energy production (Ramage et al., 2017a). Ortega-Pacheco, Keeler, and Jiang (2019)) studied competition between land use to maintain forests for carbon mitigation and agricultural land use for palm-oil production. The authors focused on the economic motivation and highlighted the importance of forest conservation for climate mitigation. Forests provide a vast array of ecosystem services, whose tradeoffs remain partly unknown (Mori, Lertzman, & Gustafsson, 2017), but that restrict logging activities (Ranius et al., 2018). A proven method to analyze the supply of wood is the criticality assessment framework as adapted by Ioannidou, Pommier, Habert, and Sonnemann (2019)) for construction wood products. Those authors suggested estimating the economic incentive to use wood in the construction or in other sectors by calculating the indicator of "competing end uses". The present analysis assumes that biomass, which is currently available in plantations and crop lands, and which is currently not required by other sectors, could be used for construction. However, the present analysis does not consider the following factors, which could indeed put pressure on the biomass resources, and lead to a degradation of land and the ecosystem, as well as leading to an increased competition for land: global population growth that requires an increased amount of food and therefore an increased efficiency of yields and/or more land for crop farming and forestry, global warming that affects the harvest yield, a shift towards bioenergy, which would increase the demand of suitable biomass for its production (e.g. hemp), (Smith et al., 2010). Moreover, it needs to be noted that the use of woody biomass is generally recommended for climate change mitigation but controversially discussed due to the above-mentioned externalities of increased harvest (Creutzig et al., 2015; Plutzar et al., 2016), the trade-offs between biomass production and carbon sequestration of the soil, and the negative consequences of forestry on other ecosystem services such as recreational purposes of a forest (Haberl, 2015). It is generally assumed that forests are preferable to cropland due to higher soil organic carbon (Popp et al., 2014). However, Morais, Teixeira, and Domingos (2019)) found that some types of crops, depending on the location, could accumulate more soil organic carbon than forests.

There is another aspect that needs to be considered for high bulk materials when analyzing the LC-related GHG emissions: environmental impacts and costs related to transportation of raw material to the manufacturer (LC stage A2) are dependent on the density of the raw material due to the maximum volumetric load capacity of lorry (Göswein et al., 2018). Even if transportation phase was not included in the present work, this could be a disadvantage of the low-density material straw, compared to timber. However, as shown in Fig. 1, straw is available all over Europe and transport-related impacts are expected to be small. This is because even though the high potential of raw material supply at the national level does not ensure close geographical proximity of supply and demand, the chance of proximity increases, the higher the potential is.

6.3. Local material solutions

Straw- and timber-based construction technologies can be considered universal solutions for high carbon storage considering available land, at least within the EU. The analysis showed that both hemp and cork at current production level could not even meet 25 % of the construction-induced demand (refer to Fig. 7). However, that does not necessarily mean that those materials are not suitable in any of the EU-28 countries. When looking at Fig. 6, we can see that in the southern dry geocluster the supply of cork is higher than the construction-induced demand. Yet, cork is high value agricultural product that is mostly used for cork stoppers of bottles, which until now provide the highest economic return. Sales of cork stoppers are rising again with a volume increase of 3.9 percent in 2018 in Portugal, the main producer or cork (APCOR, 2019). Therefore, an increased use of cork bark for the construction product ICB is only likely if achieving a higher added value (Sierra-Pérez, López-Forniés, Boschmonart-Rives, & Gabarrell, 2016). While timber and straw could be used nearly homogeneously across the EU due to the large availability of these resources, the relationship between the building stock and the available land for hemp and cork cultivation is more complex due to a local concentration of these resources in only a few regions. In many EU territories, the relationship between urban and rural areas will become more critical with future expansions of cities and the expected emergence of new business opportunities related to the promotion of circular and local bio-material production. In this way, cork boards in southern Portugal or hemp shives mixtures in French regions, may become a key factor to preserve rural territories and create new cross-sectorial synergies within the territories.

From an environmental point of view, dynamic LCA, as a more realistic impact assessment method which includes timing of emissions (Demertzi, Paulo, Faias, Arroja, & Dias, 2018), shows that prolonging the lifespan of the cork product, e.g. by using it in a building instead of as a short-lived cork stopper, reduces its carbon footprint due to delayed emissions at the end-of-life.

6.4. *Providing the right legal framework*

The use of any of the studied construction technologies at a large scale remains unrealistic until a promoting legal framework is provided. Yet, there is a promising trend at the political level to recognize the potential for climate change mitigation of bio-based construction. The Bioeconomy Strategy issued by the European Commission recognizes the potential of wood construction for the reduction of GHG emissions (EC, 2018). In France, for example, since 2010 the use of timber or other natural materials is required in new construction and starting from 2022, all new public buildings need to be constructed with minimum 50 % of natural materials (Errard, 2020). Moreover, the markets for mass timber construction are growing in Austria, Germany and Sweden (Kremer and Symmons, 2015).

Even though the analysis showed that the current amount of supply is insufficient to meet the demand in any Geocluster, hemp offers various opportunities: the here studied construction material hempcrete is made with water, binder (cement), and hemp shives. The latter being a by-product of hemp cultivation (Carus & Sarmento, 2016a). Hemp can also decontaminate polluted soils (Linger, Müssig, Fischer, & Kobert, 2002). This makes the plant a great choice for brownfield development, meaning to restore areas that suffered from industrialization (Rizzo et al., 2015) and nowadays have no use although often located in strategic areas for urban development. Moreover, hemp cultivation only requires little fertilization and the harvest is biannual. Yet, due to the psychoactive ingredients, particularly because of Tetrahydrocannabinol (THC), in cannabis species, hemp cultivation is still limited in most countries. Even though the cultivation of industrial hemp with low levels of THC (e.g. cannabis sativa) has been legal since 1989 (EEC, 1989), and EU community is now starting to open the door to future softer limitations, the strict conditions and controls make farming difficult. However, during recent years France, Italy and other countries of the EU are decriminalizing cannabis use for recreational purposes (Ledsom, 2019). Thus, also affecting the access and availability of industrial hemp, leading for example to almost a full supply in France (Carus & Sarmento, 2016b). If this trend continues, hemp could be used extensively for regenerative cultivation of brownfields. According to report by the European Commission, in 2005 across Europe, 500,000 ha of brownfield land were available for development (European Commission, 2013). The largest brownfields can be found in Germany, the United Kingdom and France (F. Pittau et al., 2014). These areas, if existing contamination and risks allow, provide a huge land resource for example for hemp cultivation. Besides the obvious benefit of brownfield development, using hemp for this purpose would also increase the amount of the by-product hemp shives, to be used in construction. Moreover, there is no obstacle of inducing land use competition in those areas since before the regeneration the land was unusable for any type of cultivation.

6.5. *Technical feasibility*

All studied construction technologies are feasible from a technical perspective. However, for cultural and economic reasons their large market implementation seems unrealistic at this moment in time. This study adds to the findings of Lauk, Haberl, Erb, Gingrich, and Krausmann (2012)) that analyzed socioeconomic carbon stocks, including buildings, and concluded that at the current growth rate socioeconomic carbon stocks do not offer major potential for climate change mitigation. The most common concerns regarding bio-based construction materials are aesthetic function and aging, durability, hydrothermal performance especially under humid conditions, and fire performance (Jones & Brischke, 2017). Moreover, their application in high-rise buildings is limited nowadays in many countries due to limitations in fire regulation. The key here is the right application. The design and construction with and of bio-based materials requires specific knowhow. For example, applying thermal insulation internally instead of externally eliminates the risk of reducing structural and aesthetic qualities due to weathering. Reaction to fire and fire resistance can be improved for example through specific coatings (Lucherini, Razzaque, & Maluk, 2019). Nevertheless, to achieve large-scale use of any of those materials while maintaining a sustainable management of forests and crops, a political framework and incentive would be needed (Ramage et al., 2017a).

6.6. *Limitations of the study and future outlook*

The proposed model consists many uncertainties in all four parts. For the built environment system, these uncertainties include the renovation rates, potential future changes of energy codes, changing lifestyle habits of residents (Rodrigues & Freire, 2017). Moreover, the exact structure of the bio-based construction technologies has a considerable impact on the material demand. As for the industrial processing system, raw material requirement that are based on the construction material production can vary considerably by location and producer. Within the carbon balance system, the exact modelling of carbon emissions though harvesting, processing and constructing, especially for wood products, can lead to differing results (Lippke et al., 2011). Local availability, transportation distances and efficiencies have a considerable impact on the embodied carbon emissions (Göswein et al., 2018). The natural environment system faces uncertainties when it comes to data accuracy and future cultivation development, especially regarding the data used for modelling the straw and cork supply, which is based on many assumptions (see SI Annex C). Forest managements vary significantly in the different EU-28 countries but there is a clear tendency towards fully sustainable management (FOREST EUROPE, 2015), which results in longer rotation periods than the ones considered in this work. These issues should be addressed through sensitivity analysis in future studies.

Future research should include the exclusion of demolition and reconstruction of buildings. In addition, the chosen time frame of 30 years should be extended to be more in line with the long lifespan of buildings (Aksözen, Hassler, & Kohler, 2017) and long rotation periods of forests (Guest, Cherubini, & Strømman, 2013).

7. Conclusions

The present study estimated the land use consequences of a radical shift towards bio-based construction materials. Four alternative construction technologies, made with wood (TIM), straw (STR), hemp (HEM) and cork (ICB), for new construction and renovation of the European building stock until 2050 were analyzed. For this purpose, the evolution of the European building stock was modeled. The resulting annual required construction material was converted into raw biomass and the corresponding required land was analyzed. Additionally, the cumulative potential of storing carbon in the building stock by 2050 was calculated and linked to the relative land use of biomass supply to estimate the space efficiency of each technology alternative. The analysis showed that the amount of land currently available for growing wood and straw is sufficient in every European region (Geocluster) to meet the future evolution of the building stock. Contrarily, the land currently available to grow hemp and cork is only sufficient to supply locally the processed materials and the creation of a large-scale supply-chain, as of today, is not feasible. The results allow to draw the following policy-relevant conclusion, keeping in mind that the present analysis did not consider the potential impacts of the increased biomass harvest on the ecosystem equilibrium:

- Straw can be strongly recommended for large-scale construction and renovation since it has the highest cumulative carbon storage potential until 2050. Moreover, it is a by-product of wheat farming whose only use is animal bedding. Using it for construction would not change the amount of land used or the intensity of wheat production. It would, however, provide additional economic value to farmers.
- Wood is the most promising in terms of space efficiency (relative highest carbon storage in buildings while occupying the smallest amount of land). Also, an advanced infrastructure network is already developed for timber supply in Europe. Yet, since other sectors are also shifting towards increased use of wood, it is likely that there will be increased resource competition. Moreover, it needs to be noted that the consequences of an increased wood harvest on the biodiversity and carbon sequestration of the soil were not analyzed.
- Hemp is not sufficiently available across the Geoclusters. The land needed for hemp shives production covers only 2% of the whole demand and its future development is currently limited in many countries by stringent legislations. This means that only a marginal amount of carbon could be stored in the European building stock if using HEM. Moreover, hemp is also interesting for the bio-economy, which is likely to increase its demand of hemp in the future. Yet, at a local level, hemp might be interesting for brownfield regeneration of degraded land and to stimulate the local economy.
- Cork is only locally available in southern dry regions. Only 4% of cork can be supplied for building insulation due to the low coverage of oak savannas, which leads to a small potential carbon storage potential in the building stock. The raw material cork has comparably high economic value and it is extensively used in the wine-producing industry. Yet, at the local level, in Portugal, it is a promising alternative from an environmental point of view since ICB is a local and all-natural thermal insulation.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

The authors would like to thank José Dinis Silvestre for his invaluable help and for drawing attention to insulation cork boards. They also wish to express their gratitude to Martha Demertzi and Luís Gil for sharing their expert knowledge of the Portuguese cork industry. Verena Göswein acknowledges the support of the CERIS Research Centre, Instituto Superior Técnico, Universidade de Lisboa, and of FCT (Fundação para a Ciência e a Tecnologia), that supported her PhD with the PD/BD/127854/2016 scholarship.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2021.102929.

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