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Wood products in the bioeconomy

Scenario-based assessment of the potential for engineered wood products in climate change mitigation

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Abbreviations

BAU	business-as-usual
CCF	continuous cover forestry
CLT	cross-laminated timber
CO_2	carbon dioxide
COVID-19	coronavirus disease 2019
EFI-GTM	Global Trade Model
EU	European Union
EU-27	European Union with its 27 member states as of February 2020 (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands (Kingdom of the), Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden)
EU-28	European Union with its 28 member states, 2013–2020 (EU-27, United Kingdom)
EV	electric vehicle
EWP	engineered wood product
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization of the United Nations Statistics
FASOM	Forest and Agricultural Sector Optimization Model
FFSM	French Forest Sector Model
FOROM	FOrest Resource Outlook Model
FRA	Global Forest Resource Assessment
FSC	Forest Stewardship Council
GDP	gross domestic product
GFPM	Global Forest Products Model
GHG	greenhouse gas
GLOBIOM	Global Biosphere Management Model
Glulam	glue-laminated timber
GTM	Global Timber Model
HDF	high-density fibreboard
HWP	harvested wood product
IEA	International Energy Agency
IGSM-CAM	Integrated Global System Model-Community Atmosphere Model

IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LAC	Latin America and the Caribbean
LCA	life cycle assessment
LVL	laminated veneer lumber
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MDF	medium-density fibreboard
MMCF	man-made cellulosic fibre
NDC	Nationally Determined Contribution
NorFor	Norwegian Forest Sector Model
NPP	net primary productivity
OECD	Organisation for Economic Co-operation and Development
OSB	oriented strandboard
PEFC	Programme for the Endorsement of Forest Certification
PVC	polyvinyl chloride
RCP	Representative Concentration Pathway
SAF	sustainable aviation fuel
SDG	Sustainable Development Goal
SSP	shared socioeconomic pathway
UBA	German Environment Agency
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
USDA	United States Department of Agriculture
USITC	United States International Trade Commission
WEC	World Emissions Clock

Units

EJ	exajoule (10^{18} joules)
Gt	gigatonne (one billion tonnes)
ha	hectare
kg	kilogram
m	metre
mm	millimetre
Mg	megagram (1000 kg, or 1 million grams)
Mt	megatonne (1 million tonnes)
t	tonne
y	year

Executive summary

Introduction and methods

The forest sector is an integral part of the global bioeconomy, and it is rapidly evolving, driven by changes in the global demand for wood products. The built environment is a major user of wood products, spurred by the imperative to decarbonize the construction sector and the increased use of structural engineered wood products (EWPs) for use in multi-storey buildings, in addition to traditional wood frame construction. Together with a growing interest in biofuels, biochemicals and cellulosic textile fibres, this shift could reshape wood product markets and supply chains, while also transforming the building sector from being a major greenhouse gas (GHG) emitter into a key player for global climate change mitigation.

The forest-based bioeconomy – grounded in production, utilization, conservation and regeneration of forest goods and services – presents an opportunity for sustainable growth, diversified incomes, increased social security, greater regional cooperation, and better climate change mitigation. Heightened emphasis on wood product use in the built environment could reap additional benefits in terms of reducing the sector's carbon footprint and avoiding the catastrophic consequences of global warming.

This report seeks to understand the implications of these trends by examining how global wood product demand could evolve in the future, in relation to the projected increased demand for EWPs. The report uses the FOrest Resource Outlook Model (FOROM), a partial equilibrium model designed to analyse the global forest sector, including forest resources, timber supply, demand for intermediate and final products, and trade flows. The model does not capture the impacts of changes in the forest sector on the broader economy, and dynamic prices were not investigated. The model adopts an additional demand shift for sawnwood to represent increased EWP demand and explores various scenarios for future use of EWPs and how this increased demand will be supplied until the year 2070. The scenarios are relatively conservative in their future EWP demand by capping the maximum model EWP for urban residential construction adoption rate at 30 percent (in contrast to 50 to 90 percent in other studies). The scenarios include different assumptions regarding the share of people living in urban areas, amount of living space per person, and amount of wood used per square metre of floor space, in comparison with a business-as-usual (BAU) scenario where there is no additional adoption of EWPs. The model also looks at how moderate and high warming climate change scenarios might affect forest productivity and wood supply capacity.

To gain a preliminary understanding of the climate change mitigation potential of future demand for EWPs, the report estimates the potential carbon storage and substitution effects (i.e. emissions reductions) of the EWP demand projected by FOROM. The report also compares emission reductions at the country level with a select number of national climate change mitigation targets such as the Nationally Determined Contributions (NDCs), which outline a country's plans to reduce emissions.

Context

Five megatrends play a key role in reshaping global wood product markets: (1) digitalization (e.g. increasing digital communication); (2) sustainability and decarbonization initiatives; (3) growing urbanization and demand for building materials; (4) shifting energy use (e.g. increasing demand for bioenergy); and (5) innovations and technological advancements in the forest sector (e.g. technological advancements in EWPs, man-made cellulosic fibres). These trends vary across world regions. For example, sustainability and decarbonization tend to play a lesser role in the Asian and African forest sectors, while urbanization is a much larger driving force in these regions.

In terms of supply, approximately half of global industrial roundwood is supplied by naturally regenerating forests, with planted forests accounting for the rest. Planted forests are expected to produce an increasing share of roundwood supply, although the extent to which they can meet future demand for wood products is influenced by multiple factors. These include, among others, national and international policies, sustainable forest management practices, and land-use competition. Furthermore, projections on future wood product supply and demand vary depending on modelling approaches and scenarios used.

Key findings

Increased urban adoption of EWPs in residential building construction could increase future demand for EWPs by around 50 (low urban adoption) to 250 million m^3 (high urban adoption) globally in any given year between 2030 and 2070. Because of increased wood use, regional supply–demand imbalances are anticipated to intensify. In 2050, under a medium urban adoption scenario, Asia would require an additional 40 million m^3 coniferous sawnwood, almost a 30 percent increase from current production levels, while Africa would require nearly 20 million m^3, representing an increase of 165 percent from current production levels.

These findings reflect the heterogeneity in urbanization and wood adoption rates, with demand growth varying widely across regions.[1] Rapidly urbanizing regions such as Asia and Africa are anticipated to experience the largest increases in EWP demand, while already urbanized markets like Europe and North America are anticipated to respond by adjusting production, reallocating wood to different uses, and expanding trade.

Climate change will unevenly affect forest productivity by mid-century. Under both the moderate and high warming scenarios, forest productivity is anticipated to increase in some regions (e.g. parts of Europe, Asia) and show only marginal changes in others (North America, South America and Oceania). This suggests an enhanced capacity for some regions to supply wood if forests are maintained and well managed. The effects of interacting disturbances on climate impacts and potential species shift are not represented in the model.

As wood use and demand rises, traditional exporter regions may become importers. Under a high warming scenario, North America is projected to shift from a net exporter to a net importer of industrial roundwood, with production declining by 60 million m^3 in 2050. In contrast, Europe is projected to become a stronger exporter, with industrial roundwood exports rising by about 60 million m^3 under the high warming scenario in 2050. This reversal reflects the combined effects of rising demand and climate-driven changes in forest productivity and competitiveness. Under Representative Concentration Pathway (RCP) 8.5, productivity declines push North America into a net import position, while Europe's relative gains support higher production and a stronger export role.

Expanded use of EWPs can deliver important global carbon emission reductions. Carbon storage and substitution effects are two ways in which increasing EWP use could help cut emissions. Under a medium demand scenario of EWP use, in which the urban adoption rate is 20 percent higher than the BAU scenario, global annual emissions could be reduced by 236 $MtCO_2$-eq per year for the period 2025 to 2070 compared

[1] Regional results presented in this study describe FOROM modelling regions (Table A2 and Table A3) rather than political or FAO data regions.

with BAU, with a cumulative total reduction of 10.9 $GtCO_2$-eq for the same period. While equivalent to less than 1 percent of the annual and cumulative emissions projected globally for the same period, these remain important potential contributions. The high urban adoption rate scenario (30 percent) could achieve 50 percent higher emission reductions than the medium demand scenario.

Across all scenarios, carbon storage accounts for at least 61 percent of the cumulative emission reductions, with substitution effects accounting for the rest (39 percent).

At the country level, the trends in annual emission reductions of projected increased EWP use and the contribution towards national climate change mitigation targets vary. With regards to national climate change mitigation targets, the relative contribution of cumulative emission reductions from future EWP demand is mixed, ranging from less than 3 percent of emission reductions targets (e.g. Germany) to potentially surpassing current mitigation targets (e.g. Nigeria). It should be noted that the estimated emission reductions are dependent on the factors used to derive carbon storage and substitution effects, which are highly specific to geographical contexts and product life cycle stages considered.

Conclusions and outlook

This study shows that even with conservative estimates, urban adoption of EWPs could drive a substantial increase in global wood demand, with strong regional differences in both supply potential and climate benefits. Policymakers and practitioners therefore face both challenges and opportunities in promoting the transition towards a forest-based bioeconomy through the increased use of wood in construction. The following recommendations could help address the projected supply–demand imbalances for wood products, while also leveraging their climate change mitigation potential.

Adopting principles of material efficiency and circularity could ensure that demand for wood products can be sustainably met, closing supply–demand gaps with minimal need for additional harvesting. This could entail, for example, diverting wood products from short-life applications towards long-life uses (including construction), developing end-of-life management strategies that enhance the recovery of post-consumer wood products, and promoting sustainable and resource-efficient forest management practices.

Maintaining international trade in global forest resources can balance regional supply and demand. Keeping global trade networks open and accessible between regions can enable efficient flows of wood products from surplus regions to deficit regions. These trade flows in wood products need to be aligned with sustainability standards and strong governance frameworks to ensure forest conservation and restoration.

Considering integrating the anticipated changes in wood product markets and their implications for climate change mitigation into bioeconomy, climate, and other sectoral strategies. This could include embedding wood-based solutions in construction, energy and industrial value chains. At the same time, meeting anticipated growth in demand for wood products will need to be in line with policies to conserve and protect naturally regenerating forests for biodiversity, ecosystem services and climate change mitigation.

Looking ahead, the transition to a forest-based bioeconomy will demand coordinated action. EWPs in construction can significantly support climate change mitigation, but only if demand is managed responsibly through sustainable supply, efficient use, international trade and fair distribution. Success will depend on early, integrated policies that address regional imbalances, climate risks and governance. Choices made now will determine whether EWPs advance a sustainable bioeconomy or intensify pressures on forests.

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1 Introduction

1.1 Motivation for this report

The transition to a bioeconomy (an economy based on renewable biobased resources), sustainable production and circular material flows is central to global decarbonization efforts. Replacing fossil-based inputs with biobased alternatives (sourced from wood, bamboo or agricultural by-products) can reduce greenhouse (GHG) gas emissions, enhance resource efficiency and create new opportunities for rural and regional development. Within this broader shift, the forest-based bioeconomy plays a pivotal role. Through sustainable forest management and the cascading use of wood, it can substitute high-carbon materials in construction, packaging, textiles and chemicals; store carbon in long-lived products; and valorize residues for bioenergy and biochemicals. This transformation is being driven by factors such as growing attention towards sustainability, urbanization, digitalization, innovation in forest products, and shifts in energy systems, though the influence and interplay of these drivers vary across regions.

The built environment is a major contributor to material demand, driven by growing urbanization and income growth (Schandl *et al.*, 2024). The built environment is also a major contributor to global GHG emissions, accounting for 37 percent of global energy and process-related emissions in 2022 (UNEP, 2024). Innovation to replace carbon-intensive construction materials with less carbon-intensive products such as engineered wood products (EWPs) could, however, transform the construction sector into a major player for global climate change mitigation (Churkina *et al.*, 2020; D'Amico *et al.*, 2021), while also reshaping wood product markets and supply chains (Hurmekoski *et al.*, 2022).

The forest-based bioeconomy is rapidly evolving, partly driven by changes in global demand for wood products. For instance, traditional uses of wood in the production of pulp, paper and conventional building materials are being complemented by innovative applications like EWPs in building construction, bioenergy and advanced biomaterials. The increased use of EWPs and more generally the increased use of wood in the construction sector will likely have a significant impact on global wood supply chains and markets, as demand for these products could replace or overtake traditional uses. Increased demand for wood for construction could also strain current wood supply chains and place more pressure on extraction from forest lands. The interactions between these shifts in demand and other wood product markets, as well as the larger implications on the global carbon balance of such a transformation, are unclear.

The complexity of these transformations, therefore, necessitates sophisticated analysis to understand their implications for forest resources, livelihoods, market dynamics, ecosystem services, as well as climate change mitigation. Understanding these implications is crucial for policymakers and practitioners working on the development of a sustainable forest-based bioeconomy. While there is already a wealth of research covering various aspects of the bioeconomy transition, there remains a gap in terms of how a transformation to a forest-based bioeconomy and its climate impacts could be shaped by future demand for wood-based construction products.

This report seeks to address this gap by examining how global EWP demand could evolve by 2070, building on the FOrest Resource Outlook Model (FOROM) and the shared socioeconomic pathways (SSPs)[2] of the

[2] For more information on SSPs, see Riahi *et al.* (2017).

Intergovernmental Panel on Climate Change (IPCC). The report is structured as follows:

- Chapter 2 begins with an overview of the concepts behind a forest-based bioeconomy. It follows with an outline of the methodological framework, assumptions and scenarios underpinning the FOrest Resource Outlook Model (FOROM). It then presents the theoretical frameworks used in estimating the climate change mitigation potential of EWPs in relation to global annual emission reductions and carbon budgets, before describing the preliminary analytical approach used in this report.
- Chapter 3 analyses the relevant literature on current and future markets (demand megatrends) and on the current and future supply potential for wood products. The chapter pays particular attention to wood product use in the construction sector, while also highlighting regional trends in wood product markets and supplies. The chapter also highlights the importance of good data in decision-making, while pointing out current data gaps related to the role of wood products in the built environment in the context of a forest-based bioeconomy and climate change mitigation.
- Chapter 4 presents the results of the FOROM model through 2070, highlighting the potential shifts in market shares of wood product end uses, through its focus on demand shocks arising from various scenarios of engineered wood utilization in construction. The scenarios look at how quickly cities adopt wood, how much floor space people will need, how much wood is used per square metre of floor space, and how climate change might affect forest productivity. The results showcase, among other things, the role of trade in ensuring that future demands for wood products are sustainably met in different world regions. Furthermore, the results demonstrate the potential shifts in real demand and consumer preferences beyond historical patterns, particularly in regions like sub-Saharan Africa, where economic growth and urbanization may drive new dynamics in wood products.
- Chapter 5 presents the results of a preliminary analysis of the climate change mitigation potential of an increased future demand for wood products in the built environment, based on the theoretical frameworks and approach outlined in Chapter 2. In particular, the chapter quantifies the carbon storage and substitution effects (i.e. emissions savings) of future demand for EWPs, and how they relate to projected changes in annual emission reductions and global carbon budgets. The preliminary analysis is done at the global scale and for four case study countries to contextualize the potential climate benefits.
- Chapter 6 concludes with recommendations to policymakers and practitioners, with the overall aim of adding transparency, creating a common understanding of key data along the wood product value chain, and promoting confidence among all stakeholders on the scientific basis to further advance the forest-based bioeconomy.
- Chapter 7 contains a glossary, defining some of the key terms used in this report.

1.2 Defining the forest-based bioeconomy

The Food and Agriculture Organization of the United Nations (FAO) defines the forest sector as "the wide range of activities related to sustainable forest management, the provision and production of timber and other wood and non-wood forest products, the protection of forest ecosystems and biodiversity, and safeguarding the benefits of forests". Thus, it encompasses all activities involving forests, as well as agroforestry, and diverse stakeholders, including governments, civil-society organizations, the private sector, Indigenous Peoples, vulnerable and marginalized communities, youth and women (FAO, 2024).

The forest sector typically involves the production of solid wood products from roundwood such as sawnwood, wood-based panels, furniture and EWPs, as well as pulpwood as a feedstock for secondary products such as paper and packaging (FAO, 2022a). In its contextual analysis of wood value chains, this study also covers novel and emerging non-construction wood products such as sustainable aviation fuels, biochemicals and man-made cellulosic fibres (MMCFs) to illustrate potentially competing demand pulls for wood products from downstream users. Production chains often traverse multiple countries, with by-products like woodchips, sawdust and other residues feeding into pulp, panels and biomass energy (Jonsson *et al.*, 2021). Thus, the sector functions as an interconnected system in which processing streams generate inputs for other product categories and shifts in supply and demand in one segment affect others (Hurmekoski *et al.*, 2018; Ollikainen, 2014; see also Figure 2.1).

Forest resources, goods and services are key for bioeconomy development. FAO has adopted the following working definition of the bioeconomy based on the 2020 Global Bioeconomy Summit Communiqué: "the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy" (IACGB, 2020). Definitions of the bioeconomy vary by context. However, key drivers of a sustainable bioeconomy include resource availability, biotechnological research and development, economic growth, consumer demand for sustainable products, and supportive policy and legislation (Hassegawa *et al.*, 2022; Hurmekoski *et al.*, 2018). It also encompasses improvements in human well-being and social equity, creation and continuation of decent and sustainable jobs, and betterment of food security (IACGB, 2020).

Adopting forest-based bioeconomy approaches that sustainably use forests to produce wood products, the focus of this report, can contribute to climate change mitigation. Wood-based materials are renewable, store carbon over their life cycle, and often require less energy to produce than fossil-based alternatives. Long-lived wood products can substitute carbon-intensive materials (e.g. steel and concrete), while sustainable forest management that ensures regeneration and safeguards biodiversity maintains carbon sinks. Residues from wood processing can also displace fossil fuels in energy generation, supporting broader decarbonization goals (FAO, 2024; Hurmekoski *et al.*, 2018).

1.3 The case for wood in the built environment

The opportunity. Wood has been a dominant construction material for centuries, valued for its mechanical properties, light weight and ease to shape (Smith and Snow, 2008). Rapid urbanization during the 20th century required stronger materials for the mid- and high-rise buildings in inner cities, leading to the widespread use of concrete and steel. However, both concrete (Miller and Moore, 2020) and steel (Hasanbeigi *et al.*, 2016) are energy intensive to produce, resulting in much higher embodied emissions when compared with biobased materials (Cabeza *et al.*, 2013). Though decarbonization pathways exist for both (Cao *et al.*, 2020; Driver *et al.*, 2024), they face scaling challenges due to economic, environmental and social concerns (Fennell *et al.*, 2022; Creutzig *et al.*, 2024).

Continued urbanization trends coupled with a growing population suggest a doubling of the urban population by 2050. In practical terms, this means that half of the future cities still need to be built, mostly in Asia and Africa (UN, 2019), presenting a challenge but also an opportunity for the building sector to become a driver for the use of circular and low-carbon building materials, including sustainably sourced wood products (UNEP, 2023).

Recent trends in urban structural growth patterns suggest that cities will be increasingly dense, favoring vertical (higher buildings) over horizontal (urban sprawl) growth (Frolking *et al.*, 2024). In a business-as-usual (BAU) world this would further increase the demand for mineral-based building materials. However, with recent advances in structural EWPs it is now feasible to build mid- and even high-rise buildings from "mass timber" (Nepal *et al.*, 2024), which offers a double-carbon benefit (Churkina *et al.*, 2020) when compared with steel and concrete.

The technology. EWPs are defined as wood products that are manufactured by gluing or fixing the strands, particles, fibres, veneers or boards of wood together (Ding *et al.*, 2023) such that they have enhanced properties compared with natural wood. *Non-structural* EWPs are long established and include plywood, oriented strandboard (OSB), particle board and medium-density fibreboard (MDF), all of which have a wide range of uses in construction, furniture, flooring, soundproofing, and others. In contrast, "mass timber" (the focus of this report and from here on referred to as EWPs) comprises a group of *structural* EWPs that are laminated from smaller boards or lamella into larger structural components such as glue-laminated (glulam) beams or cross-laminated timber (CLT) panels (Churkina *et al.*, 2020). EWP production long focused on improved structural performance but more recently also demonstrates better thermal, optical and energy-related properties (Ding *et al.*, 2023). EWP-based buildings also show excellent resilience to seismic activity, both in timber-only (Pei *et al.*, 2024) and hybrid (timber and concrete) solutions (Pan *et al.*, 2021).

The combination of these properties allows EWPs to directly substitute for steel and concrete in construction. The optimum height is often described in the range of 6 to 12 storeys, which corresponds to the building height recommended for livable sustainable cities (e.g. IRP, 2018; Resch *et al.*, 2016). Yet even high-rise buildings can be built using EWP (Ilgin, 2024). Continued innovations such as laminated veneer lumber (LVL) and dowel-laminated timber broaden the range of possible applications and increase the reusability and recyclability of EWP components and materials.

EWP elements are fabricated offsite and assembled at the construction site (Smith *et al.*, 2018). Moving the prefabrication offsite increases the productivity in construction by reducing the time of building construction while improving project cost when compared with traditional site-built construction (Smith *et al.*, 2018). The use of structural timber is complemented by non-structural biobased materials from either forest origin (by-products from, for example, wood processing for use as insulation, infills, and others), fast-growing plants and agricultural by-products (Göswein *et al.,* 2022).

The benefits. Building with EWPs rather than with carbon-intensive materials provides a double carbon benefit through substantially reducing the emissions from material production and the opportunity for long-term carbon storage potential in buildings (Churkina *et al.*, 2020; see also Section 2.2). For forests, a reliable, strong demand for sustainable wood products allows long-term investing in sustainable forest management practices, with positive effects on the carbon sequestration capacity, particularly in the case of increasingly disturbed forests (Pett-Ridge *et al.*, 2023). From a building user perspective, the integration of "nature elements" (such as wood) into architecture can lead to enhanced health and improved well-being and productivity (Zhong *et al.*, 2022).

The construction of EWP buildings is generally associated with less impact on the building's surroundings than from conventional building construction. For example, building with EWPs can avoid the substantial water use associated with concrete (Varshney *et al.*, 2021). Their use can also lead to much shorter construction times (Abed *et al.*, 2022) and fewer traffic interruptions and associated emissions. EWP buildings still face an overall cost premium because of higher material costs than concrete (Ahmed and Arocho, 2021) but the gap closes with scaled and improved manufacturing technology (Abed *et al.*, 2022). However, labour costs during construction are lower because of offsite manufacturing, making the assembly of buildings much faster (and quieter) than conventional buildings. The corresponding job displacement in the construction industry is more than compensated by job growth in the EWP manufacturing industry, substantially strengthening regional economies (Abed *et al.*, 2022).

Because wood is a lightweight material, structural EWPs are uniquely qualified to densify inner cities (Kremer *et al.*, 2024) as they allow the addition of lightweight wooden storeys on top of existing buildings, mostly without the need to reinforce foundations or other building structures. This allows the sustainable extension of useful building lifetimes without disturbing the character of inner cities.

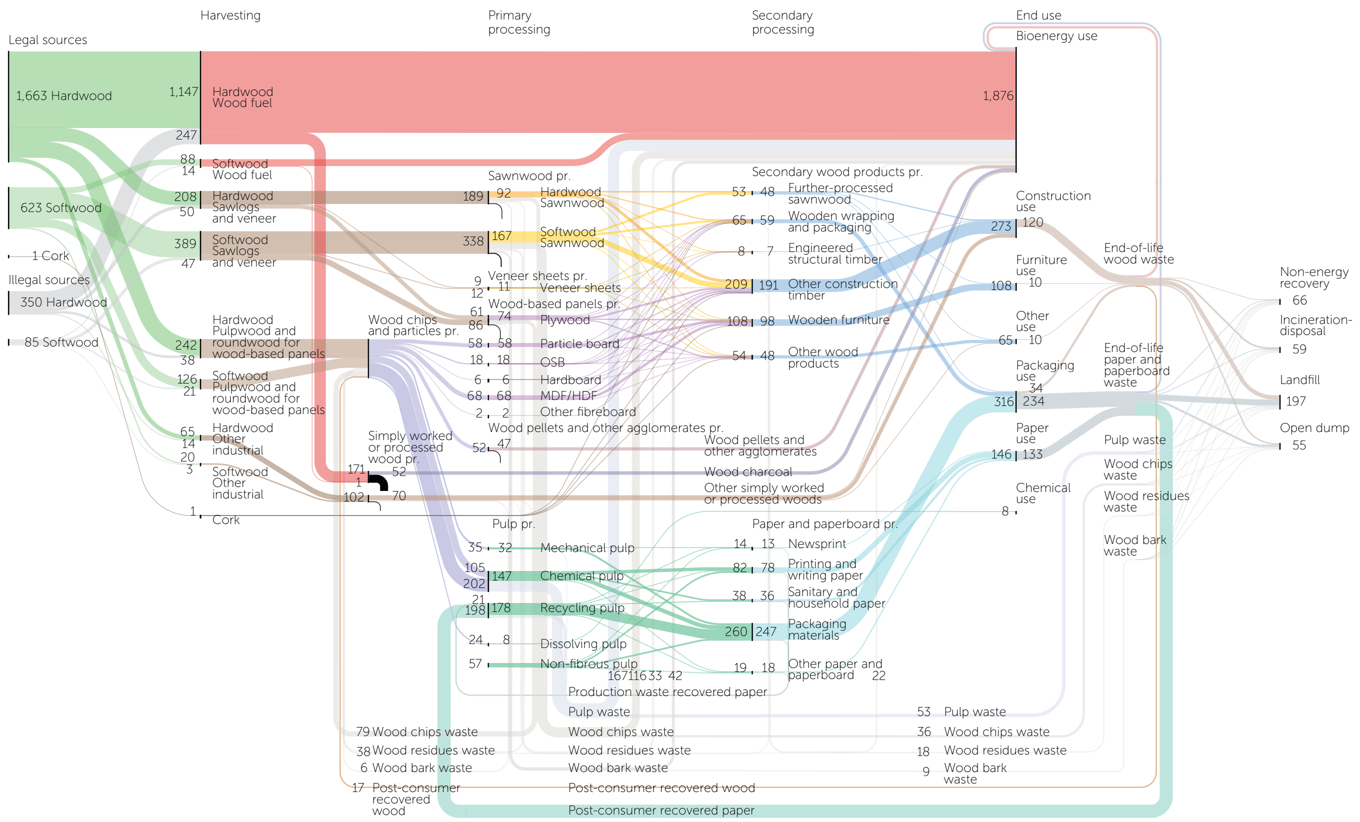
2 Concepts and methods

This section introduces the analytical framework used to model potential impacts of a bioeconomy transition on the global forest sector, focusing on one potential pathway: the increased use of wood in construction for its climate benefits. The analysis focuses on potential greater use of engineered wood products (EWPs) in construction, in particular the increasing use of cross-laminated timber (CLT) and glue-laminated timber (glulam) in building construction.

The chapter begins by reviewing forest sector models and their evolution. It then describes the FOrest Resource Outlook Model (FOROM; Johnston *et al.,* 2021), including its data, structure, and enhancements for capturing global interactions and climate impacts. The rationale for selecting FOROM for this study in comparison to other existing models, particularly for addressing questions of urban wood adoption and climate impacts, is explained. It then introduces the scenario design framework used to explore future wood product demand and supply under varying urban adoption rates, floor area expansion, and climate trajectories through 2070.

The material cycle of wood products and woodfuel is complex (Figure 2.1) (Yayla *et al.,* 2025), extending from the harvest of hardwoods and softwoods, through primary and secondary processing, use as wood products or woodfuel, and end-of-life management (including recycling). FOROM models wood products from production of roundwood and sawnwood to their end use in construction, paper and packaging, and other sectors.

Figure 2.1 Global flow of wood from forests to end use and recovery in 2021



Notes: Global wood cycle for 2021 from harvesting to processing, end use, and end-of-life treatment including recycling. All values are in million oven-dry tonnes. *Source*: Yayla *et al.* (2025).

Source: Yayla, A., Mason, A.R., Wang, J., van Ewijk, S. and Myers, R.J. 2025. Global wood harvest is sufficient for a climate-friendly transition to timber cities. Nature Sustainability, 8: 1013–1025. https://doi.org/10.1038/s41893-025-01605-w.

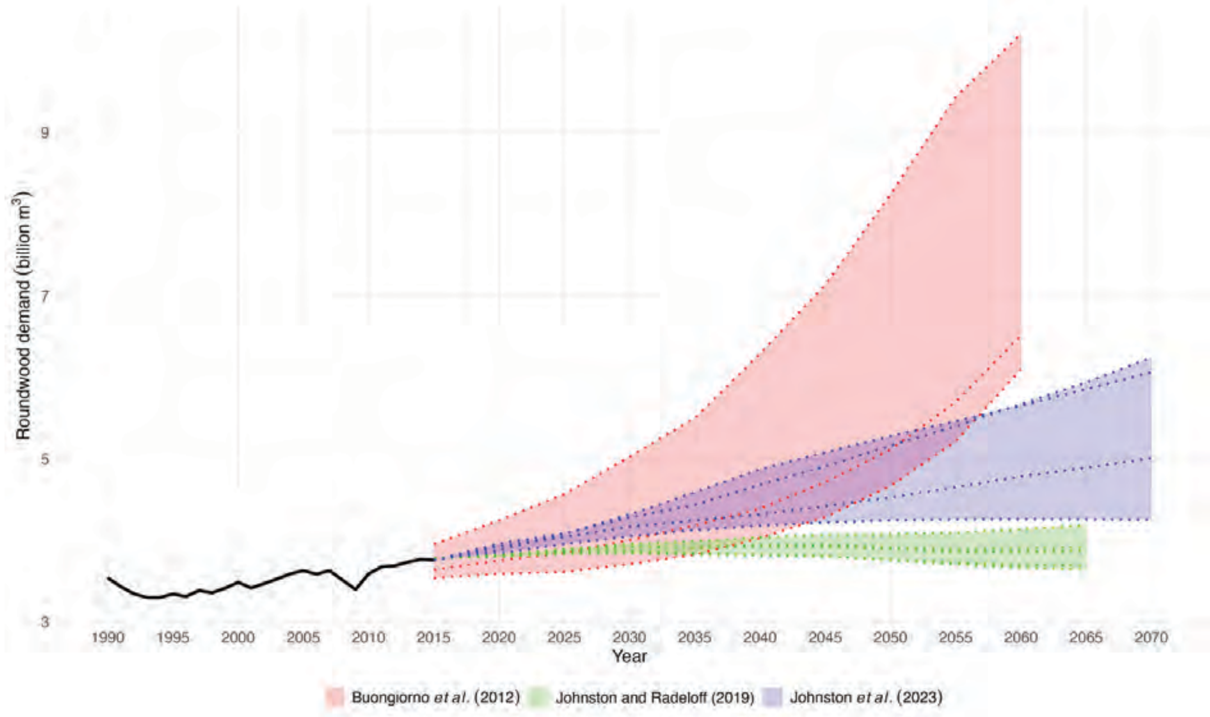
2.1 Review of supply and demand studies on wood products

Research studies on global wood supply and demand projections present different results depending on modelling approaches and scenarios. Longer-term projections show greater variation, reflecting increased uncertainty over extended time horizons. The review of these studies provides background information and identifies gaps in knowledge, thereby informing the projection analyses presented in Chapter 4.

2.1.1 Projection of global roundwood demand

Alternative scenarios provide projections of annual global roundwood demand ranging from 3.6 to 11.2 billion m^3 (Figure 2.2). This substantial variation is due to the different methodological frameworks and scenario assumptions used in the different studies, reflecting the complexity of modelling long-term forest sector developments.

Figure 2.2 Global total roundwood demand, 1990–2070



Note: Scenario results are reported through 2060 in Buongiorno *et al.* (2012) and through 2065 in Johnston and Radeloff (2019).

Source: Buongiorno, J., Zhu, S., Raunikar, R. and Prestemon, J.P. 2012. Outlook to 2060 for world forests and forest industries: A technical document supporting Forest Service 2010 RPA assessment. USDA Forest Service, Southern Research Station. https://doi.org/10.2737/SRS-GTR-151, Guo, J., Prestemon, J. and Johnston, C. 2023. Forest market outlook in the southern United States. Forest Policy and Economics, 157: 103091. https://doi.org/10.1016/j.forpol.2023.103091.

The Global Forest Products Model (GFPM) (Buongiorno *et al.* 2012) has been a predominant analytical tool. Successive studies have refined projections by incorporating new elements such as biofuel use, lignocellulose-based products, and other wood products as well as by incorporating improved understanding of key drivers. This model has been widely used because of its detailed representation of international trade flows, extensive country coverage, and flexibility for policy analysis.

The progression in modelling approaches has led to increasingly nuanced projections. FOROM's integration of climate scenarios with socioeconomic pathways provides a more comprehensive view of potential future developments (further information in Section 2.1.4 and Chapter 4). Table 2.1 provides a summary of global roundwood demand projections, along with key variations and assumptions.

Table 2.1 Global roundwood demand and forest area projections from select studies

Model (source)	Projections for demand and planted forest area (including plantation)	Key variations and assumptions
GFPM (Buongiorno *et al.*, 2012, 2003)	Total roundwood consumption (industrial and woodfuel) reaches 6.1–11.2 billion m^3 by 2060 or 3.7 billion m^3 in the low woodfuel scenario. Woodfuel accounts for 90% of total roundwood consumption by 2060 or 40% in the low woodfuel scenario.	IPCC scenarios (A1B, A2, B2 and A1B low fuelwood) include global and regional economic activity, population, land uses, and greenhouse gases and biofuel consumption. For scenarios A1B, A2 and B2, global fuelwood consumption grows as predicted by IPCC biofuel scenarios: 5.5 times for A1B, 2.7 times for A2 and 2.9 times for B2.
GFPM (Johnston and Radeloff, 2019)	Roundwood consumption is projected to remain at 3.6–4.2 billion m^3 by 2065. Industrial roundwood consumption increases by 19% to 53% by 2065 compared with 1.8 billion m^3 in 2015. Annual net removals from harvested wood products are estimated to peak around 2030 at 317–415 $MtCO_2$.	SSP1–5 include socioeconomic changes to project forest area, forest stocks and demand for wood products, with a particular focus on carbon storage in HWPs as part of climate change mitigation.
GFPM (Nepal *et al.*, 2019)	Industrial roundwood production increases by 1% compared with 2015, but the share of planted forests in total roundwood production increases from 46% to 65% by 2070. Global planted forest area is projected to increase from 293 million ha in 2015 to 379–475 million ha by 2070. According to SSP2, planted forest area increases by over 45% in Africa, Asia and South America, and by less than 29% in Europe, North America and Oceania.	SSP1–5 include variations in GDP growth, population and forest sector policies. Assumptions include higher growth rates in planted forests compared with natural forests, driven by increased productivity and investment in planted forestry. The model considers feedback between planted forest area and roundwood production.
GFPM (Morland and Schier, 2020)	Roundwood consumption increases to 4.3–5.5 billion m^3 by 2050. Industrial roundwood production changes by −5% to up to 120%. The latter largely due to increased demand for wood-based panels and lignocellulose-based products. Woodfuel use decreases by 32% in the "Change" scenario. The "Islands" scenario projects moderate growth. The "Drip" scenario assumes limited growth in the bioeconomy, resulting in a 30% increase in woodfuel use.	The scenarios include SSP1 (Change), SSP4 (Islands) and SSP2 (Drip) with different levels of sustainability including woodfuel consumption and technological progress. "Change" focuses on green innovation and global cooperation, "Islands" on regional disparities, and "Drip" reflects limited bioeconomy adoption.

Model (source)	Projections for demand and planted forest area (including plantation)	Key variations and assumptions
GFPM (Held *et al.*, 2021)	Roundwood production increases to 4.3 billion m^3 by 2050. Industrial roundwood production increases by 45% by 2050.	"Middle-of-the-road" scenario (SSP2), assuming moderate socioeconomic and technological growth. Plantation forestry becomes the main source of roundwood production (i.e. 73% of industrial roundwood from plantation sources in tropical regions by 2050), with Southeast Asia and Latin America emerging as leading regions in this transition. Natural forests maintain a reduced but stable role. Agroforestry and smallholder systems are playing an increasing role in production, particularly in tropical regions.
Planted forest area model (Korhonen *et al.*, 2021)	Global planted forest area is projected to increase from 293 million ha in 2015 to 319–334 million ha until 2045–2055. Planted forest area decreases from 2055 to 2100. Africa shows the largest increases in each SSP scenario, while Asia and South America show modest growth.	SSP2, SSP3 and SSP5 include variations in GDP growth, population, forest sector policies, rural population density, labour per forest area, and capital per forest area.
MAgPIE (Mishra *et al.*, 2021)	Global plantation area projected to increase by 177% in the period 1995 to 2100. China's plantation area is projected to account for 40% of the global plantation area in 2100. Plantations contribute an increasing share of industrial roundwood production, growing from 328 to 1583 million m^3/year between 1995 and 2100.	MAgPIE includes detailed representations of forest land, timber production and demand dynamics, and is based on SSP2, which provides assumptions for GDP and population growth. MAgPIE accounts for competition for land between agriculture, forestry and other uses and assumes a heterogeneous age-class structure of forests at initialization.
FOROM (Johnston *et al.*, 2023)	Roundwood consumption achieves 4.4–6.6 billion m^3 by 2070. Industrial roundwood production is 52% to 76%. Softwood roundwood consumption recovers to pre-recession levels by 2020 and continues to grow, while hardwood consumption grows at a higher rate (USDA Forest Service, 2023).	Projections are based on SSPs and climate models (RCPs). Scenarios capture varying levels of GDP growth, population dynamics, trade openness, technological advancements and energy transitions.

Notes: FOROM = FOrest Resource Outlook Model; GDP = gross domestic product; GFPM = Global Forest Products Model; HWP = harvested wood product; IPCC = Intergovernmental Panel on Climate Change; MAgPIE = Model of Agricultural Production and its Impact on the Environment; RCP = Representative Concentration Pathway; SSP = shared socioeconomic pathway.

Source: Authors' own elaboration.

2.1.2 Review of forest sector models

Forest sector models are essential tools for understanding the complex interactions within the sector, including supply and demand dynamics, market mechanisms, policy impacts and ecological processes. This review examines the historical development, methodologies, applications and future directions of forest sector models, focusing on the FOrest Resource Outlook Model (FOROM).

Early models such as the Faustmann (1849) Model were primarily focused on optimizing harvest schedules to maximize profits. While foundational, these models were simplistic and static, lacking the ability to account for broader sectoral dynamics. As environmental concerns grew and global demand for forest products expanded in the 1970s and 1980s, more elaborate models emerged. For instance, the Global Trade Model (EFI-GTM), developed by Kallio *et al.* (1987), simulated international timber trade while incorporating transportation costs and trade barriers. By the 1990s and 2000s, advancements in computational power and data availability enabled the development of dynamic and geographically based models, such as the Global Forest Products Model (GFPM) (Buongiorno, 2003, 2015) and the Global Biosphere Management Model (GLOBIOM) (Lauri *et al.*, 2019). These models enhanced understanding of interactions between forest ecosystems, economies and societies, offering valuable insights for sustainable forest management.

Forest sector models generally fall into two categories based on their methodological approaches: (1) recursive dynamic models, and (2) intertemporal optimization models. Recursive dynamic models solve market equilibrium sequentially, period by period, where each period's solution informs the next. These models typically rely on short-term expectations, where decision-makers base their choices on current market conditions without fully anticipating future developments. They are computationally tractable and flexible, making them suitable for analysing global market dynamics and policy impacts. Examples include the GFPM, which covers in its basic form 180 countries and 14 forest product categories. GFPM's strength lies in its detailed representation of international trade flows, including transportation costs and tariffs. However, it has little to say about forest management decisions and environmental services. Another example is GLOBIOM, a global recursive dynamic model, which allows for spatially explicit modelling of land use, including agriculture, forestry and bioenergy production on a moderately high-resolution basis. Biophysical processes can be integrated using satellite biophysical models that account for factors including productivity under varying soil, climate and management conditions. In addition, the TiMBA model (TI-FSM *et al.*, 2025; Carus *et al.*, 2025) is also a recursive, dynamic and global model for 180 countries. It can distinguish up to 19 forest products including two emerging product groups of the growing bioeconomy, namely lignocellulose-based chemical derivatives and textile fibres (both made from dissolving pulp).

National-level recursive dynamic models, such as the French Forest Sector Model (FFSM) (Caurla *et al.*, 2010), bridge detailed forest resource dynamics with market behavior. FFSM incorporates forest owner decision-making, regional heterogeneity and climate change impacts on forest growth but since it is a national forest sector model, FFSM faces limitations in geographic scope as well as representation of non-market ecosystem services.

In contrast, intertemporal optimization models account for future market conditions and forward-looking behavior of decision-makers. These models optimize outcomes across multiple periods simultaneously, enabling strategic analysis of resource management and investment decisions. For example, the Global Timber Model (GTM) incorporates age-class dynamics, endogenous technological change and strategic forest management behavior, enabling an evaluation of long-term carbon sequestration potential and climate change impacts (Sohngen *et al.*, 2001). However, intertemporal models like the GTM are computationally complex and often simplify regional or product details and may assume fixed optimal rotations.

The Forest and Agricultural Sector Optimization Model (FASOM) integrates forest and agricultural land-use decisions within an intertemporal optimization framework (Alig *et al.*, 2002). It captures land-use competition and its implications for greenhouse gas (GHG) emissions, making it valuable for analysing climate policy impacts. However, its complexity limits its geographic and temporal resolution.

Similarly, national-level intertemporal models, like the Norwegian Forest Sector model (NorFor) (Sjølie *et al.*, 2011), analyse detailed forest management alternatives and their implications for carbon sequestration and timber production. But such national models face geographic constraints and challenges in linking to international markets when characterizing the effects of large domestic or foreign structural changes or economic shocks.

Recent advancements have focused on hybrid modelling approaches, which integrate forest sector models with other analytical tools, such as computable general equilibrium models and integrated assessment models. These linked systems allow researchers to explore sectoral analysis with economy-wide interactions and feedback. Similarly, integrating FASOM with agricultural sector models enhances the analysis of land-use competition and the trade-offs between agricultural expansion and forest conservation.

2.1.3 Overview of FOROM – A forest sector model

The FOrest Resource Outlook Model (FOROM) represents a significant advancement in forest sector modelling (Johnston *et al.*, 2021). It builds on previous frameworks like GFPM, employing a recursive dynamic partial equilibrium approach to capture interactions between forest resources, timber markets, and a detailed representation of international trade flows including transportation costs and tariffs. As a partial equilibrium model it does not, however, capture the impacts of changes in the forest sector on the broader economy and does not incorporate dynamic pricing. Compared with the basic version of the GFPM, FOROM offers enhanced product coverage, representing 20 distinct forest products. This detailed breakdown enables thorough analysis of how regional markets function while maintaining awareness of global trends.

Recent applications of FOROM highlight its utility in addressing pressing policy and market questions. It has been used to analyse the expansion of EWP (mass timber) markets, projecting how increased demand might influence forest resources, trade flows and sustainability efforts (Nepal *et al.*, 2021). FOROM has also been used to assess the implications of natural disturbances, such as storms and hurricanes, on timber availability and prices (Johnston *et al.*, 2024), helping stakeholders mitigate associated economic risks (Guo *et al.*, 2023). Additionally, the model has been applied to evaluate the global wood pellet market under various energy policy scenarios, examining how policies promoting renewable energy could drive demand and affect forest resources (Johnston *et al.*, 2022).

FOROM is designed to analyse the global forest sector, including forest resources, timber supply, demand for intermediate and final products, and international trade. It simulates supply, demand, trade and prices across multiple product categories and regions, using detailed representations of production costs, resource availability and end use demand. The model determines market-clearing prices by maximizing the sum of consumer and producer surplus subject to constraints on resource use, trade flows and capacity. This welfare-optimizing framework ensures that projections of production, consumption, trade and prices reflect economically efficient allocation of resources across the global forest products sector.

FOROM is primarily calibrated using 2015 data from FAOSTAT (FAOSTAT, 2025), with additional inputs from the United States Department of Agriculture (USDA) Forest Service's Timber Product Output program and the United States International Trade Commission (USITC). The model's main objective is to evaluate how production, consumption, trade, and pricing of raw materials, intermediates, and final goods, as well as forest land area and standing stock, may respond to external factors such as economic growth, climate change, trade policy shifts or forest management practices.

FOROM represents the global wood product market through 20 interconnected product categories (Table A1) across 55 countries and regions (Table A2 and Table A3), capturing intricate relationships within the sector. EWPs are not explicitly represented in the model, so it is assumed that an increased demand for, or use of, EWPs is the same as an increased demand for sawn timber. The model incorporates several key assumptions to forecast future trends. Economic and population growth drive demand, with changes in gross domestic product (GDP) per capita influencing both market dynamics and the marginal costs of production through adjustments in forest area and standing inventory. Technological advancements are also factored in, to account for improvements in the efficiency of converting raw materials into finished products, while trade openness reflects the friction associated with the movement of goods between regions.

To account for the impact of climate change on forest productivity, FOROM integrates projected changes in net primary productivity (NPP) to adjust forest growth rates within FOROM. NPP projections, simulated to 2070 at a 0.5-degree resolution, are obtained from the MC2 dynamic global vegetation model based on climate inputs including precipitation, temperature, vapor pressure and atmospheric CO_2 concentrations (Kim *et al.*, 2017). These projections use climate data produced by the MIT Integrated Global System Model-Community Atmosphere Model (IGSM-CAM) under Representative Concentration Pathway (RCP) 4.5 and RCP8.5 climate change scenarios (Monier *et al.*, 2013). NPP projections output by MC2 are aggregated into 16 global land units, with annual trends translated into changes in forest productivity relative to baseline growth rates for each region. Note, disturbances and potential species shift are not well represented in the current set of climate change scenarios, and temperature change across scenarios do not vary much before 2050.

Further details on FOROM's mathematical structure, data inputs and sources are provided in Johnston *et al.* (2021). It is important to acknowledge limitations and uncertainties in forest sector models like FOROM that affect its projections. For example, FOROM's outputs depend on assumptions about timber demand, land-use change, climate impacts and policy interventions, all of which carry uncertainty. Structural limitations arise from how forest growth, management and disturbances interact over time, while socioeconomic assumptions (e.g. GDP growth, population, technology) introduce variability in forecasted harvest levels. The model is particularly sensitive to price elasticities, harvest costs, regeneration rates, and uncertainties related to climate change impacts leading to different long-term outcomes. Additionally, climate change impacts on productivity and data uncertainties in inventory estimates and disturbance projections affect accuracy. Given these challenges, scenario analysis and sensitivity testing are essential for interpreting results and understanding the range of possible forest resource futures.

2.1.4 Simulating future demand for wood products in the built environment

This study aimed to investigate ways in which demand for EWPs used in building construction may increase beyond what might be predicted from historical patterns and from projected economic growth. To do so, we investigate how shifts in urbanization, construction practices and material usage, combined with population growth, contribute to increased demand for wood products in building construction, potentially beyond what traditional models based on GDP growth alone can predict. Details on the continent-based FOROM modelling regions are provided in Table A2 and Table A3.

In order to simulate this in FOROM, an additional driver of demand was constructed for sawnwood of species type k (i.e. coniferous, non-coniferous), to represent increased demand for EWPs in building construction:

$$additional\ demand_{i,t}^{k} = \Delta pop_{i,t} * urban\ rate_{i,t} * adopt_{i,t} * floor\ area_{i,t} * wood\ use\ intensity_{i,t} * share_{i,t}^{k} \quad (1)$$

where the change in demand for wood products is driven by several factors:

- Δ*pop* represents changes in population in region *i* at time *t*, which influences the overall demand for housing and, by extension, construction materials.
- *urban rate* reflects the percentage of the population living in urban areas, where building construction is more intensive and reliant on wood products.
- *adopt* is the assumed rate of adoption of EWPs in residential building construction methods in urban development, which is particularly important as the adoption of technologies like glulam and CLT, for example, increase.
- *floor area* represents floor area per capita, which directly affects the demand for materials per individual.
- *wood use intensity* is the amount of wood required per square metre of construction, reflecting changes in building practices and material efficiency.
- *share* represents the share of total domestic sawnwood production in the region sourced from coniferous or non-coniferous trees. This is calculated based on a recent historical share of production from coniferous and non-coniferous sawnwood. This parameter indicates that EWPs will be produced using a similar hardwood–softwood mix as for sawnwood production in each region.

Assumptions related to these parameters and climate scenarios used to assess future demand for EWPs in building construction are outlined in Table 2.2. In the *business-as-usual* (BAU) scenario, it is assumed there is no additional adoption of EWPs. The *medium adoption* scenario assumes a 20 percent urban adoption rate of EWPs, medium floor area and medium wood use intensity. The *low adoption* scenario considers a lower urban adoption rate of 10 percent, with medium floor area and wood use intensity, while the *high adoption* scenario increases the urban adoption rate to 30 percent, maintaining medium floor area and wood use intensity. It is important to note that this study's 30 percent "high" EWP adoption rate is conservative when compared with the 60 to 90 percent found in the literature (see Table 2.3). The *low floor area* scenario assumes a 20 percent urban adoption rate, but with low floor area and medium wood use intensity, while the *high floor area* scenario has the same adoption rate but assumes high floor area with medium wood use intensity. In the *low wood intensity* scenario, the urban adoption rate remains at 20 percent, with medium floor area and low wood use intensity, which increases gradually over time. Conversely, the *high wood intensity* scenario follows the same adoption rate and medium floor area but assumes high wood use intensity with a gradual increase.

Climate scenarios

The *reference*, *RCP4.5* and *RCP8.5* scenarios (van Vuuren *et al.,* 2011) incorporate climate change assumptions. The reference scenario represents a world consistent with current climate change. RCP4.5 is an intermediate warming scenario in which GHG concentration is stabilized mid-century through mitigation efforts, and RCP8.5 is a high warming scenario without effective global GHG mitigation. The two climate scenarios are used together with 20 percent urban adoption rates, medium floor area, and wood use intensity assumptions to assess the impact of climate change on forest production and use. These scenarios are based on socioeconomic assumptions aligned with shared socioeconomic pathway (SSP) 2 (Riahi *et al.,* 2017), which reflects moderate development and urbanization trends. They help to explore how urbanization, construction practices and climate change might influence future demand for wood products.

Table 2.2 Scenarios and scenario parameters

Scenario	Urban adoption rate (capita)	Floor area (m^2/capita)	Wood use intensity (m^3/m^2)	Climate (RCP)
BAU	None (0%)	---	---	Reference
Medium adoption	Medium (20%)	Medium	Medium (0.4)	Reference
Low adoption	Low (10%)	Medium	Medium (0.4)	Reference
High adoption	High (30%)	Medium	Medium (0.4)	Reference
Low floor area	Medium (20%)	Low	Medium (0.4)	Reference
High floor area	Medium (20%)	High	Medium (0.4)	Reference
Low wood intensity	Medium (20%)	Medium	Low (0.4 – 0.6%/y)	Reference
High wood intensity	Medium (20%)	Medium	High (0.4 + 0.6%/y)	Reference
RCP4.5	Medium (20%)	Medium	Medium (0.4)	RCP4.5
RCP8.5	Medium (20%)	Medium	Medium (0.4)	RCP8.5

Notes: Scenarios are based on socioeconomic assumptions aligned with SSP2 from the International Institute for Applied Systems Analysis (IIASA) (Riahi *et al.*, 2017). For the wood intensity scenarios, +/–0.6%/year growth is assumed such that the 0.4 starting assumption grows or decays to 0.2 and 0.6 in the low and high wood intensity scenarios respectively by 2070, to represent the range found in the literature. More details can be found in the wood use intensity section. Floor area rates across low, medium and high scenarios for 2015 to 2070 from Fishman *et al.* (2021), based on their LED (low), SSP1 (medium) and SSP2 (high) scenarios. Urban adoption rates are author-assumed values for residential buildings. BAU = business-as-usual; RCP = Representative Concentration Pathway; SSP = shared socioeconomic pathway.

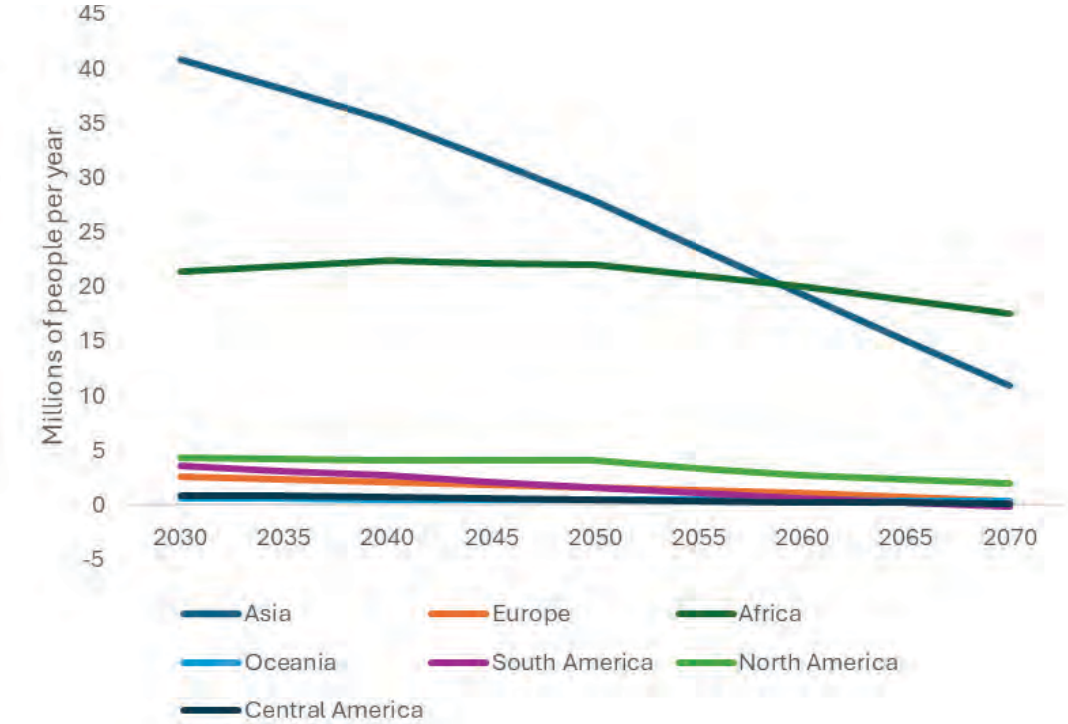
Source: Authors' own elaboration.

Effects on engineered wood product adoption: Urban population change

Among the continent-based modelling regions (Table A2 and Table A3), Asia will continue to have the highest urban population growth, peaking at around 40 million people per year and then gradually declining (Figure 2.3). Africa also shows significant growth, with its population increasing steadily, though at a slower rate than Asia during the earlier part of the century. Europe, North America, South America and Central America show relatively stable or slightly slowing population growth over the forecast period. Oceania also experiences minimal changes.

The connection to the scenario of increased wood product demand lies in how urban population growth, especially in regions like Asia and Africa, will drive demand for building construction and, consequently, EWPs. In regions with high rates of urban population growth, such as Asia and Africa, the need for housing and urban development will likely lead to a higher demand for construction materials, including wood-based products (Grand View Research, 2025). Conversely, stable or declining urban populations in regions like Europe may not see the same level of growth in domestic demand for wood products and new housing, although factors such as urban adoption rates and wood use intensity could still influence their domestic demand for wood products. However, these regions, including Europe, may increase their wood products production to satisfy expected higher import demands from Asia and Africa.

Figure 2.3 Annual change in urban population by region in SSP2 scenario, 2030–2070



Source: 2.3 Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., ONeill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. and Tavoni, M. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42: 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Amount of engineered wood product per person: Floor area rates

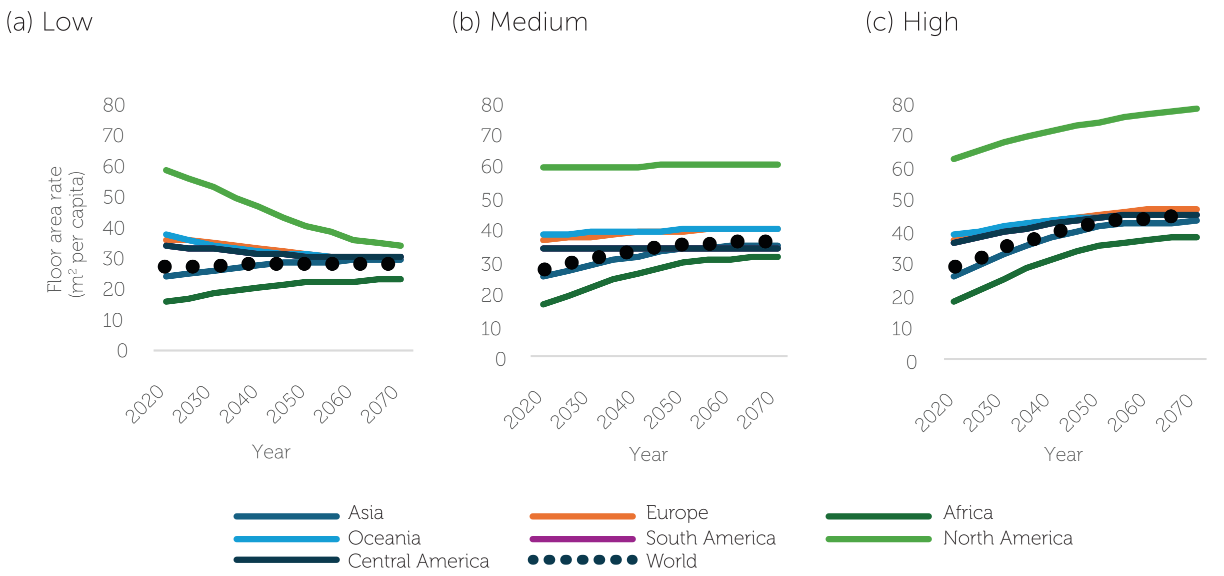
The projected evolution of floor area per capita is investigated under three scenarios – low, medium, and high – based on different socioeconomic pathways (low energy demand [LED], SSP1 and SSP2, respectively), reported in Fishman *et al.* (2021). The low scenario assumes modest economic growth and a focus on minimalistic housing, leading to the lowest per capita floor area expansion (Figure 2.4). The medium scenario represents moderate growth, consistent with global historical trends. In contrast, the high scenario anticipates accelerated economic development and urbanization, resulting in the highest floor area per capita by 2070.

These projections highlight significant regional variations, with developed regions maintaining high floor area rates and emerging economies experiencing rapid increases, particularly in the high scenario. The trends underscore how socioeconomic conditions and urban planning policies could substantially impact future demand for construction materials, particularly wood-based products like sawnwood and EWPs.

Effects on engineered wood product use: Wood use intensity per unit floor space

The amount of wood usage per unit of floor space (e.g. m^3/m^2) in EWP-based construction varies substantially across different countries and regions. Various factors can influence wood usage per unit of floor space, including local regulations such as building codes and standards, economic factors such as availability and cost, and existing green building policy and incentives aimed at reducing carbon footprint of the built environment. The use of EWPs also varies by building type (e.g. residential versus nonresidential) and by building height (low versus mid- to high-rise buildings). Studies have reported a wide range of EWP (mass timber) use intensities across different parts of the globe, ranging from as low as 0.04 m^3/m^2 (Mitsui Fudosan, 2024) to as high as 0.85 m^3/m^2 (Basterra *et al.*, 2023). However, the average wood use intensity in most EWP buildings worldwide is estimated to range from 0.2 to 0.4 m^3/m^2 (Basterra *et al.*, 2023; Nepal *et al.*, 2024; Taylor *et al.*, 2023).

Figure 2.4 Floor area rates across low, medium and high scenarios, 2015–2070



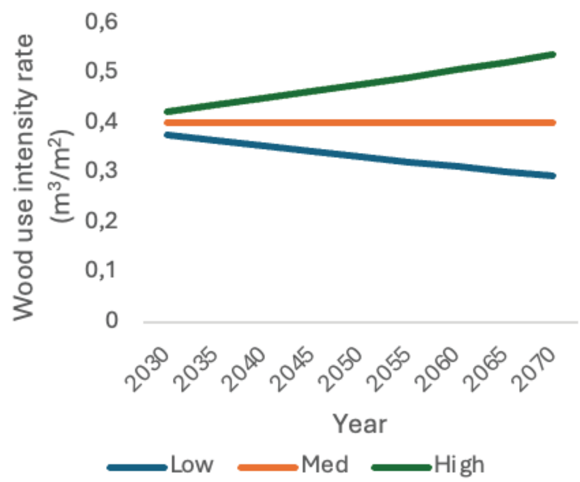
Notes: Low = Low energy demand (LED) scenario; Medium = SSP1 scenario, 1; High = SSP2 scenario.
Source: Fishman *et al.* (2021).

Source: Fishman, T., Heeren, N., Pauliuk, S., Berrill, P., Tu, Q., Wolfram, P. and Hertwich, E.G. 2021. A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modeling. Journal of Industrial Ecology, 25(2): 305–320. https://doi.org/10.1111/jiec.13122.

For example, in the United States of America, the estimated EWP use in 16 mass timber buildings sampled by Taylor *et al.* (2023) was 0.23 m^3/m^2. Other studies estimated US average EWP (mass timber) usages of 0.26, 0.33 and 0.24 m^3/m^2 for 4 to 6, 7 to 12, and higher than 12 storey buildings, respectively (Nepal *et al.*, 2024). Similarly in Europe, a study of wood usage in 28 multi-storey timber buildings higher than four floors examined by Basterra *et al.* (2023) in southwest France, Portugal and Spain, and 101 worldwide buildings (mostly in Europe), indicated average wood usage intensity between 0.3 and 0.4 m^3/m^2. Hurmekoski (2017) suggested that the wood use intensity of wood construction in the European Union (EU-28) can be assumed to vary from 0.2 m^3/m^2 (light frame) to 0.6 m^3/m^2 (massive frame). Wood use intensities in EWP buildings in other countries such as Australia, Canada and Japan are reported to fall within the range estimated for Europe and the United States. It is important to note that most of the available data refer to the northern hemisphere, and important differences may be observed for other regions of the world. However, due to data limitations, those differences are not considered.

Based on our current understanding of wood use intensity in EWP buildings as described above, Figure 2.5 highlights the assumed cubic metres of wood required

Figure 2.5 Assumed wood use intensity rates across low, medium and high scenarios, 2030–2070



Notes: Low = Low energy demand (LED) scenario; Medium = SSP1 scenario, 1; High = SSP2 scenario.

Source: Authors' own interpretation.

per square metre of floor area, under low, medium and high scenarios. The low scenario assumes technological advancements and efficiency improvements in construction methods, leading to reduced wood use per square metre. The medium scenario represents moderate adoption of wood-based materials, maintaining current trends. The high scenario reflects increased reliance on wood-intensive construction techniques, driven by policies promoting sustainable and carbon-neutral building practices.

Wood use intensity shows a gradual divergence across the scenarios, with the high scenario emphasizing the potential for greater demand for sawnwood and EWPs. These variations underscore the importance of construction practices and material substitution in shaping future wood product demand.

2.2 Climate change mitigation potential of wood products

This section provides an overview of the theoretical background, methodologies and assumptions used in estimating the climate change mitigation potential of wood products. Specifically, this section discusses the concepts of carbon storage and substitution benefits, which are used to quantify climate change mitigation potential, as well as global carbon budgets and their use in determining national climate targets.

2.2.1 Emissions, carbon storage and substitution effects of wood products

Understanding the climate change mitigation potential of wood products can be considered in terms of their direct or indirect emission reductions, and how they compare with future emission projections. In the built environment, wood products can contribute to climate change mitigation in two ways: (1) carbon storage in wood products, and (2) material substitution effect (Arehart *et al.*, 2021). However, the extent to which wood products are estimated to contribute depends on the models used, as well as the methodological assumptions, system boundaries and time frames that are considered in carbon accounting. For this reason, different studies have produced different narratives and conclusions on potential carbon benefits (or costs) of increasing forest harvests and wood product use (Table 2.3), with no global consensus on the topic.

Table 2.3 Model parameters and select carbon-related results of four global studies exploring increased engineered wood product adoption

Study/Methodology	Churkina et al. (2020)	Mishra et al. (2022)	Yayla et al. (2025)	Lan et al. (2025)
Timeline (t_0-t_{end})	2020–2050	2020–2100	2021–2100	2021–2100
Wood products	EWP	EWP	EWP	CLT
Urban adoption rate scenarios (%) [1]	10, 50, 90	10, 50, 90	90 [2]	30, 60 [3]
Floor area per capita (m^2/cap)	9.2, 30, 79 [4]	30 [5]	30 [5]	Modelled [6]
Scope of emissions	Site of raw material extraction; transportation to manufacturing facilities; material manufacturing	Land use change; material manufacturing	Land use change; wood cycle processes (harvesting, primary processing, secondary processing, end-of-life), including energy use and transport	Forest biogenic carbon flows; cradle-to-grave (harvesting, primary processing, secondary processing, end-of-life)
Forest model	JSBACH [7]	MAgPIE	MAgPIE-4	GTM
Results ($GtCO_2$)				
Cumulative carbon storage by t_{end}	3.12–28.12 [8]	7.3–65	37.6	4.1–8.1
Cumulative emission reductions by t_{end} (compared to BAU)				
- related to construction materials	0.84–7.86 [9, 10]	5–19 [10]		
- related to land use change and construction materials		14.4–105.6 [10]	24	25.6–39.0

Notes:

[1] Percent of new urban population living in timber buildings.

[2] Authors explored different pathways for achieving a 90% urban adoption rate (i.e. (1) shifting wood fuel to industrial use, (2) increase forest harvesting, and (3) high circular use of wood products).

[3] Percent of global new urban construction floor area built using cross-laminated timber (CLT). Authors explored different pathways (i.e. (1) 30% by 2050, (2) 30% by 2080, (3) 60% by 2050).

[4] Based on Güneralp *et al*. (2017). 30 m^2/cap taken as business-as-usual (BAU).

[5] Based on mean floor area per capita for residential buildings and material intensities for primary structure and enclosure systems from Churkina *et al*. (2020).

[6] Authors use multi-variable regression models to project total floor areas of urban commercial and residential buildings, based on gross domestic product (GDP) per capita and urban population projections following the shared socioeconomic pathway 2 (SSP2) scenario.

[7] The model was used to estimate sustainable timber harvest and supply, but not for quantifying emissions and carbon storage (which exclusively referred to the manufacturing of construction materials).

[8] Taken directly from Supplementary Table 10 of Churkina *et al*. (2020), for primary structure and enclosure timber system, assuming floor area per capita of 30 m^2/cap.

[9] Own derivation, using values from Supplementary Table 9 of Churkina *et al*. (2020). Specifically, the sum of cumulative emissions for both steel + concrete and timber systems was calculated for each scenario assuming floor area per capita of 30 m^2/cap, and the differences between each scenario and BAU were calculated and taken as the emission reductions (see Section 9.2, Table A4).

[10] Detailed information on the source for these values can be found in Section 9.2, Table A4.

BAU: business-as-usual, CLT: cross-laminated timber, EWP: engineered wood product, GDP: gross domestic product, GTM: Global Timber Model, JSBACH: Jena Scheme for Biosphere Atmosphere Coupling in Hamburg, MAgPIE: Model of Agricultural Production and its Impact on the Environment, SSP: shared socioeconomic pathway.

Source: Authors' own elaboration.

One highly debated aspect is the type of forest management system used to produce wood. To date, many global-level studies broadly assume carbon neutrality in sustainable forest management, following the Intergovernmental Panel on Climate Change (IPCC) guidelines on reporting carbon stocks in forests (Peng *et al.*, 2023). The IPCC finds strong evidence that wood products from sustainably managed forests have lower embodied GHG emissions in their production and disposal compared with emission-intensive non-renewable materials (IPCC, 2022).

However, if wood products are sourced from forests that are not managed sustainably, there is a risk of decreasing carbon stocks, in addition to ecological impacts (IPCC, 2022; Pasternack *et al.*, 2022). Recent studies have attempted to address the question of forest management impacts on carbon fluxes. For example, Gregor *et al.* (2022) estimated the climate change mitigation benefits of various forest management options in Europe, including clearcut, coppice and replanting with different tree species, while also considering trade-offs with other ecosystem services. For the United States, Pett-Ridge *et al.* (2023) explored the carbon storage in wood products along with other carbon pools related to above ground and below ground biomass under exploitation- and regeneration-focused forest management regimes.

Based on embodied emission coefficients used in life cycle assessment (LCA) models, some studies have indicated a net reduction in overall CO_2 emissions with increasing timber use in buildings (e.g. Bergman *et al.*, 2014; Zhong *et al.*, 2021). For example, if 50 percent of new urban population were housed in timber buildings, cumulative CO_2 emissions by 2050 would be approximately five times lower compared with a scenario of only 10 percent of people living in timber buildings (Churkina *et al.*, 2020).[3] However, these studies typically only look at cradle-to-gate processes, thus excluding forest growth and harvest stages.

When considering carbon fluxes in forest biomass, forest growth and/or land-use change, conclusions on the climate benefits of forest products vary. For example, Mishra *et al.* (2022) found that if 90 percent of new urban population lived in newly built mid-rise wooden buildings, an additional 106 $GtCO_2$ could be saved by 2100. According to the authors, this is equivalent to about 10 percent of the remaining carbon budget for a 2 °C global warming limit, and considers emissions from land-use change and manufacture of engineered timber. Similarly, considering carbon pools in both forests and harvested wood products, Rüter *et al.* (2016) found that for the EU-28[4] a strong increase in wood use, most notably in construction, could cut GHG emissions by 11 $MtCO_2$-eq per year on average compared with a reference scenario for the period 2010 to 2030.[5] Furthermore, using a forest growth model representative of southern Germany, Gregor *et al.* (2024) concluded that an increased use of long-life wood products can significantly contribute to overall mitigation, especially for coniferous forests, in the medium and long term. For the United States, Oliver *et al.* (2014) included forest growth and carbon sequestration in their analysis on the emissions saved in different wood products, although they assumed sustainable, fully regulated forest management regimes.

Yet, when considering forest growth and harvests, Peng *et al.* (2023) found that harvests for short- and long-lived wood products could incur substantial carbon costs of around 3.5 to 4.2 $GtCO_2$ per year globally. The same study also found relatively smaller savings of 0.8 to 0.9 $GtCO_2$ per year when considering the substitution benefits of wood products replacing, for example, traditional bioenergy and concrete and steel. It should be noted that the study assumed all harvests to be derived entirely from clear-cutting in their model to estimate carbon costs, citing difficulties in determining harvest areas and quantities from other harvest regimes such as selective harvests. Furthermore, the study defined carbon cost as the difference between the carbon storage without future harvests and the carbon storage with harvesting and planting.

[3] Based on values reported in Supplementary Table 9 of Churkina *et al.* (2020), comparing a business-as-usual scenario with a scenario of 50 percent new buildings with timber-based primary structures and enclosures.

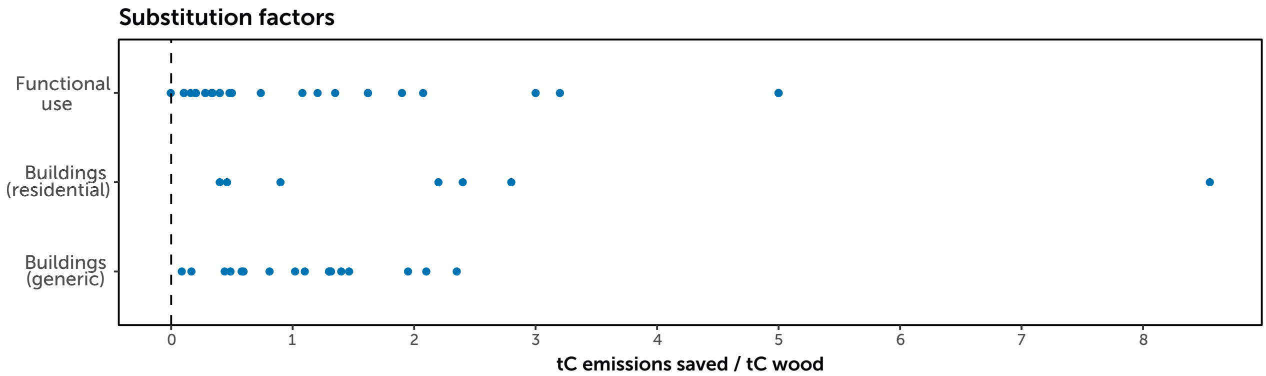
[4] The EU-28 comprises the 27 Member States of the European Union and the United Kingdom of Great Britain and Northern Ireland.

[5] The reference scenario assumes an achievement of official European Union energy and climate targets for 2020 and a continued business-as-usual trend up to 2030.

The concept of substitution benefits, proxied by substitution factors or displacement factors, has indeed become an increasingly discussed means to compare emissions between two similar products. Substitution factors tell us how many emissions could be avoided when using wood-based products as opposed to other products with the same functional end use. For the building sector, studies generally indicate substantial emission savings when using timber products. For example, a literature review by Leskinen *et al.* (2018) estimated an average substitution factor of 1.3 kilograms of carbon emissions avoided for every kilogram of carbon stored in wood products used for structural construction, 1.3 kg carbon could be saved, based on a literature review.

Substitution factors vary in terms of the GHG flows and system boundaries that are considered (Myllyviita *et al.*, 2021). Figure 2.6 illustrates the range of substitution factors for generic and residential buildings as well as specific functional end uses in buildings (e.g. walls, floorings, window frames), derived from the literature (Cardinal *et al.*, 2024; Hassegawa *et al.*, 2022; Myllyviita *et al.*, 2021; Sathre and O'Connor, 2010; Simonsen *et al.*, 2023).

Figure 2.6 Substitution factors for generic and residential buildings, and for specific functional end uses in buildings



Note: These factors were used to estimate the substitution effects of increasing engineered wood product demand under various scenarios of wood use, as described in Section 4. For details on substitution factors and their sources see Table A5 (Section 9.3).

Source: Interpretation of Cardinal, T., Alexandre, C., Elliot, T., Kouchaki-Penchah, H. and Levasseur, A. 2024. Climate change substitution factors for Canadian forest-based products and bioenergy. Ecological Indicators, 160: 111940. https://doi.org/10.1016/j.ecolind.2024.111940 , Hassegawa, M., Van Brusselen, J., Cramm, M. and Verkerk, P.J. 2022. Wood-based products in the circular bioeconomy: Status and opportunities towards environmental sustainability. Land (Basel), 11(12):2131. https://doi.org/10.3390/land11122131, Myllyviita, T., Soimakallio, S., Judl, J. and Seppälä, J. 2021. Wood substitution potential in greenhouse gas emission reduction – review on current state and application of displacement factors. Forest Ecosystems, 8: 42. https://doi.org/10.1186/s40663-021-00326-8, Sathre, R. and O'Connor, J. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science and Policy, 13: 104–114. https://doi.org/10.1016/j.envsci.2009.12.005

However, substitution factors vary in terms of the GHG flows and system boundaries that are considered, hence they should be used with caution (Myllyviita *et al.*, 2021). Critics have pointed out several other theoretical limitations that underpin substitution factors (e.g. Howard *et al.*, 2021; Leturcq, 2020). For example, Harmon (2019) postulated that, by using substitution factors, it is assumed that the carbon displacement value is constant, but this ignores trends in renewable energy uptake, technological developments and increasing energy efficiencies in the manufacture of products such as cement. Furthermore, substitution factors assume that there is no cross-sector carbon leakage (i.e. that fossil carbons displaced in one sector such as the building sector are not used and released by another sector). This is not likely as other sectors will continue to use fossil carbon as long as no mechanism is in place to permanently prevent its use (Harmon, 2019). Moreover, understanding of substitution effects of forest products is still limited due to research and data gaps at the market and country levels, such as for emerging forest products (e.g. textiles, biochemicals) and regions outside of North America and northern Europe (Leskinen *et al.*, 2018).

Regarding time frames, some studies consider time-discounting factors, which assign a higher cost to forest harvest emissions that are emitted earlier. For example, Searchinger *et al.* (2023) used an annual time-discounting factor of 4 percent, which means that one tonne of carbon emitted in a certain year is worth 4 percent more than the same amount of carbon released in the following year. This consideration acknowledges that earlier emissions can cause damage during the intervening years, while also highlighting the urgency of taking more immediate climate change mitigation measures (Hansen *et al.*, 2024; Searchinger *et al.*, 2023).

Understanding the climate change mitigation potential of wood products can also be considered in terms of carbon budgets.[6] Some climate change mitigation practitioners and policymakers have used carbon budgets as one of the key benchmarks to determine a country's mitigation targets, such as the Nationally Determined Contributions (NDCs), as well as to measure progress in reaching their targets (SRU, 2020). While helpful for guiding political decision-making in setting climate change mitigation targets, global carbon budget estimations come with several limitations. For example, they currently do not account for additional earth system feedbacks such as permafrost thawing, which can reduce carbon budgets further (Rogelj *et al.*, 2019). Furthermore, there remains a high level of uncertainty regarding land-use change emissions in deriving global carbon budgets (Friedlingstein *et al.*, 2023).

2.2.2 Preliminary analysis on the climate change mitigation potential of future engineered wood product demand

Using the projections on EWP demand from Section 4, a preliminary analysis on the climate change mitigation potential was carried out based on the carbon storage and substitution effects (i.e. emissions reductions) of future EWP demand. The analysis was carried out at the global scale as well as for two countries in the Organisation for Economic Co-operation and Development (OECD) region, Germany and the United States, and two non-OECD countries from sub-Saharan Africa, namely Nigeria and South Africa, to contextualize the climate effects with regards to country-level climate targets such as the NDCs.

This preliminary analysis is intended to illustrate carbon storage and substitution effects of a growing demand for wood products by the building sector under the various scenarios outlined in Section 4. The analysis does not consider time-discounting factors for emissions as well as carbon dynamics from forest growth and harvests, given that these are not considered in FOROM. The analysis also does not consider service lifetimes of buildings and the impacts of renovations and demolitions, as the focus is on new projected demand for wood construction products and the climate implications of such demands.

The preliminary analysis includes the following steps:

1. Estimation of changes in carbon storage: Calculated by multiplying EWP demand from Section 4 with carbon conversion factors for coniferous and non-coniferous sawnwood, which are available from IPCC (2014). Because EWPs are not explicitly represented in FOROM, this is based on the assumption that increased use of EWPs has the same effect on carbon storage as increased use of sawnwood.
2. Estimation of substitution effects of replacing conventional building materials (e.g. concrete and steel) with timber products: Calculated by multiplying EWP demand from Section 4 with substitution factors derived from various literature sources (Figure 2.6). In particular, substitution factors were selected for sawnwood that are intended for construction purposes for generic and residential buildings as well as for specific construction-related end uses such as claddings, floorings and window frames. Substitution factors that have been specified in their original sources as intended for non-residential

[6] Rogelj *et al.* (2018) define global carbon budgets as the cumulative CO_2 emissions from the beginning of 2018 (baseline period) that are allowed to be released into the atmosphere to limit global warming to 1.5 °C or 2 °C above pre-industrial levels by 2100.

buildings were excluded. Table A5 in Section 9.3 shows the list of substitution factors used and their sources.

3. Estimation of total potential emission reductions of future EWP demand for all FOROM scenarios: Calculated by summing the (1) carbon storage with (2) substitution effects, based on a common approach used by other studies in quantifying emission savings in forest product use in construction (Fehrenbach *et al.*, 2022; Kalt, 2018; Searchinger *et al.*, 2023). As the EWP demand projections are reported in 5-year time steps, linear interpolation was carried out to estimate the emission reductions for the intermediary years.

To assess and contextualize the potential emission reductions at the global level, emission reductions were compared with global emission projections from various sources. Baseline global emission projections following the SSP2 scenario were obtained from the IPCC AR6 Scenarios Database provided by the International Institute for Applied Systems Analysis (IIASA) (Byers *et al.*, 2022). As IIASA provides emission projections from various models, for simplicity, this study only uses the projections from the MESSAGE-GLOBIOM 1.0 model, which are estimated based on iterative optimization processes that enable, for example, energy demands to be satisfied at the lowest costs (Fricko *et al.*, 2017; Krey *et al.*, 2020).

Comparisons were also made with global emission projections under various scenarios of implementation of climate policies and targets provided by Climate Action Tracker (Climate Analytics and NewClimate Institute, 2024). Specifically, Climate Action Tracker's upper and lower emission pathways for the following two scenarios were used: (1) implementation of current policies and action, and (2) long-term pledges and targets (Climate Action Tracker, 2024). For the building sector in particular, the potential emission reductions were compared with sectoral emission projections from the World Emissions Clock (WEC), which include emission projections from heating, cooking and cooling in both residential and commercial buildings up to the year 2050 (WEC, 2025).

Additional comparisons of the estimated emission reductions were also made with the remaining global carbon budgets derived from Friedlingstein *et al.* (2023). Specifically, global carbon budgets that assume a 50 percent chance of achieving global warming of 1.5 °C and 2 °C above pre-industrial levels were used. As global carbon budget values were reported with 2024 as the starting year, global emission projections for the year 2024 were required to subtract the carbon budget to obtain the remaining carbon budget as of 2025 (the starting year of the preliminary analysis).

To demonstrate climate change mitigation potential of future EWP demand at a country level, the emission reductions for four case study countries (i.e. Germany, Nigeria, South Africa and the United States) were calculated and compared with each country's national level climate targets. For Germany, emission reduction targets were taken from the *Federal Climate Action Act* (Federal Ministry of Justice, Germany, 2024). For the other three case study countries, emission targets were taken from the United Nations Framework Convention on Climate Change (UNFCCC) NDC register.[7] For historical and projected emissions at the country level, data were taken from the NDC documents, German Environment Agency (UBA) (UBA, 2025), the WEC for South Africa (WEC, 2025), and the NDC documents for Nigeria and the United States.

[7] Link: https://unfccc.int/NDCREG.


clt wall panel*
elements
materials
wood
wood lamellas
99.34 %
solid wood from Galician spruces
glue
polyurethane adhesive (PUR)
0.33 %
methylene diphenyl diisocyanate (MDI), polypropyline glycol
connectors
galvanized carbon steel screws
0.33 %
iron ore, coke from oil, zinc, sulfuric Acid
-358.6 kg CO2 eq
emitted during the extraction, manufacturing and transportation of the materials composing this wall.
21 steps
are needed cummulatively to manufacture this wall panel, from extraction to assembly.
12,491.7 km
travelled by the various materials composing this wall throughout the manufacturing process.

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3 Trends in the forest-based bioeconomy

Wood product industries operate in a rapidly evolving context shaped by multiple, often interrelated megatrends within the forest-based bioeconomy. On one hand, growing emphasis on environmental sustainability and the bioeconomy fuels demand for renewable materials and low-carbon solutions that can be met by timber products. On the other hand, digitalization and urbanization are changing consumer demand and preferences, affecting longstanding value chains like traditional paper products. Innovation, technology and the pursuit of operational efficiency have sparked new value-chain configurations and competitive business models. These parallel forces sometimes intersect harmoniously but can also create challenges as industries strive to balance profitability, sustainability and innovation. This section examines these competing megatrends and their ongoing and future implications for wood product industries.

3.1 Forest dynamics by type and region

Forests can be categorized based on their type of regeneration and management intensity (i.e. naturally regenerating, planted and plantation forests) (FAO, 2023b). In 2025, the total global forest area was estimated to be 4.14 billion ha, of which 92 percent were naturally regenerating and 8 percent were planted forests (FAO, 2025). Planted forest includes approximately 50 percent of plantation forest (FAO, 2025).

Between 1990 and 2025, the area of naturally regenerating forests decreased by approximately 324 million ha, while the area of planted forests increased by 129 million ha to reach 312 million ha (FAO, 2025). This trend reflects a global increase in planted and plantation forests, alongside a reduction in naturally regenerating forest areas. Asia and particularly China experienced the highest expansion of planted and plantation forests, with North America and Europe also showing notable increases. Deforestation rates were highest in Africa and South America, with net losses exceeding several million hectares annually. However, the rate of loss slowed in the decade to 2025 in both regions (FAO, 2025; Figure 3.1).

Figure 3.1 Global and regional forest area (by type) in 1990 and 2025 and roundwood harvest (industrial use versus woodfuel) in 1990 and 2024

Notes: Top: Forest area by type (in million hectares) in 1990 and 2020. Bottom: Industrial roundwood and woodfuel harvests (in million tonnes) and type of industrial roundwood in 1990 and 2020.
Source: Own compilation based on data from FAO (2025) and FAOSTAT (2025).

The global wood supply from natural forests peaked around 1989 and has since been declining. Although an increasing share of roundwood supply is coming from planted and plantation forests (Warman, 2014), the extent to which plantation forestry can reliably meet growing demand and thereby play a role in reducing demand pressure on over-exploited natural forests is influenced by multiple factors. These include national and international policies, sustainable management practices, forest health and pest management, land-use competition, and evolving trade requirements (FAO, 2023a; UNECE and FAO, 2021a).

However, increasing the supply of wood from plantations does not necessarily reduce the loss of natural forest cover. This is particularly the case where forest management practices remain unsustainable, where natural forests have been felled mainly for the benefit of the plantation industry (Braun, 2022). At the same time, strategically establishing plantations on previously cleared or historically degraded lands can help meet future timber production needs while reducing pressure on remaining natural forests.

Natural forests provide essential ecosystem services beyond timber production, such as habitat for biodiversity and various non-timber forest products that cannot be provided by plantations (Dinh and Pham, 2023). Globally, naturally regenerating forests continue to contribute most of the industrial roundwood production, with temperate and boreal regions accounting for 44 percent, and tropical and subtropical regions contributing 9 percent in 2020. Meanwhile, about 23 percent of the global supply of industrial roundwood is provided from planted forests in temperate regions and about 23 percent from planted forests in tropical and subtropical regions (FAO, 2022b). The area and growing stock of naturally regenerating forests in temperate and boreal regions have remained stable. These forests have the potential to increase their growing stock and timber production, but climate and biodiversity policies may restrict further increases of harvest levels (Dieter *et al.*, 2020). In contrast, naturally regenerating forests in tropical and subtropical regions have experienced significant declines since 1990, a trend that continues. Yet, production volumes from naturally regenerating forests in the tropics and subtropics are expected to remain stable (FAO, 2022b).

Section 9.5 provides additional information on regional trends in forest types.

3.2 Projection of global planted and plantation forest area and wood production

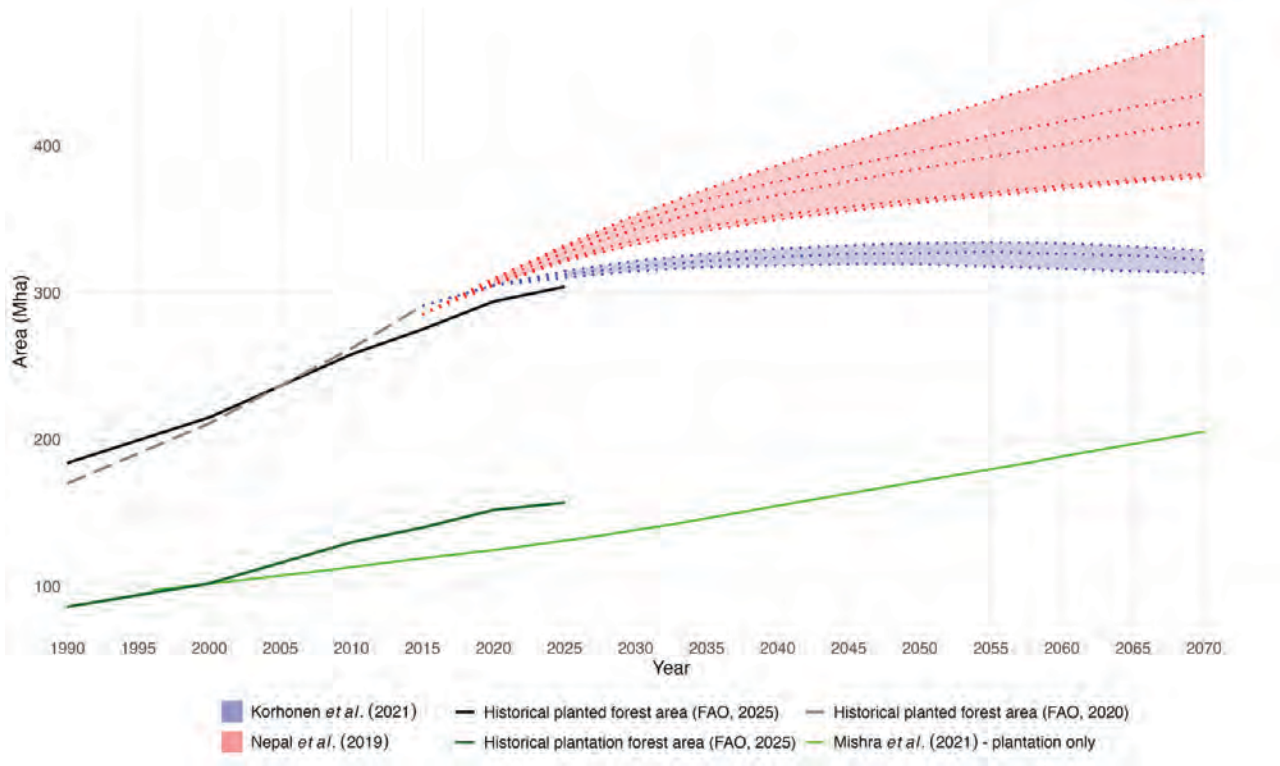
Three of the research studies reviewed in Table 2.1 suggest that future roundwood demand is projected to require a significant expansion of planted and plantation forests. FAO (2022b) anticipates that an additional 33 million ha of highly productive plantation forests will be required to meet wood demand by 2050, especially under conditions where 70 percent of future sawmill and plywood residues serve as substitutes for virgin wood fibre, and productivity rates in new plantations are optimized. Recent evidence suggests that approximately 101 million ha of abandoned cropland could be strategically allocated to either recultivation or forest regrowth globally (1992–2020). This land pool offers a plausible, spatially identifiable source for establishing new productive plantations where appropriate (Zheng *et al.*, 2023). Projections from the Model of Agricultural Production and its Impact on the Environment (MAgPIE) also highlight the growing role of plantation forests in a sustainable wood supply, given their potential for higher yields per hectare compared with natural forests (Mishra *et al.*, 2021).

Projections of planted and plantation forests differ widely across various modelling approaches (Figure 3.2, Table 2.1), depending on socioeconomic and climate assumptions and how these impact forest management. For example, Nepal *et al.* (2019) project a relatively modest increase in industrial roundwood production of 2.3 million m^3 by 2070 under a middle-of-the-road scenario (SSP2). Yet the share of production from planted forests increases significantly from 46 to 65 percent. This underlines the future importance of planted forests in meeting wood supply needs.

The findings from Korhonen *et al.* (2021) highlight how increases in per capita income and labour per unit of forest area positively influence the expansion of planted forests, while higher rural population densities tend to suppress it. Their findings also highlight regional differences in planted forest area expansion.

Mishra *et al.* (2021) project a near doubling of global plantation area by 2100 compared with 1995, driven by higher economic growth trajectories and robust demand for wood-based products. The supply of roundwood is increasingly dependent on intensively managed plantations, particularly in South America and Asia. Incorporating timber production into a global land-use model reveals that newly established plantations often compete directly with cropland in this scenario. The model indicated that displacement of agricultural land contributes to deforestation in other areas. This points to the need to better integrate trees for wood production and carbon sequestration with agricultural land uses (Keenan *et al.*, 2024).

Figure 3.2 Projected forest area for plantations and planted forests (including plantations) by research group and scenario, 2020-2070



Source: Own compilation based on Mishra *et al.* (2021), Korhonen *et al.* (2021) and Nepal *et al.* (2019). Baselines from FAO (2015) and FAO (2025).

3.3 Megatrends affecting wood-based industries

3.3.1 Digitalization

Digitalization is an ongoing, dynamic process that continues to shape industries and society. For example, the transition to digital communication platforms has significantly decreased the demand for traditional paper products, such as newsprint and printing paper. Johnston (2016) modelled the projected decline in graphic paper consumption based on global internet adoption rates, predicting a 32 to 42 percent decline in graphic paper demand and a 48 to 68 percent reduction in newsprint demand by 2050, across scenarios regarding the rate of internet adoption.

As demand for traditional paper products continues to decline, the pulp and paper industry is being steered towards opportunities in packaging and specialty papers, prompting investment in alternative value streams for wood pulp (Johnston, 2016). The COVID-19 pandemic significantly expanded e-commerce, which in turn increased demand for packaging papers. Beyond reducing paper dependency for communication, digitalization is spurring innovation in industries through improvements in energy efficiency, process optimization, advanced digital infrastructure, and big data analytics, which in some cases reduces carbon emission from manufacturing (Renn *et al.*, 2021; Yi *et al.*, 2022).

3.3.2 Decarbonization and sustainability

The imperative to preserve forest land to sequester CO_2 and conserve biodiversity resources is a consequence of international policy goals like the Paris Agreement, the Convention on Biological Diversity, and the United

Nations Sustainable Development Goals (SDGs). The resulting international attention towards sustainability, and the limited availability of petroleum-based products in the future, is driving innovation towards a bioeconomy (Hassegawa *et al.*, 2022; Hurmekoski *et al.*, 2018; Ollikainen, 2014).

Research in the last decades has revealed that there is great potential for forest products to substitute carbon-intensive building materials and other petroleum-based products, which beside substantial carbon benefits also has the potential to create significant value for actors in the forest supply chain (Graichen *et al.*, 2017; Hurmekoski *et al.*, 2018). Increased consumer awareness of sustainable alternatives to widely used commodities like energy and textiles is also shifting demand patterns in some regions of the world (Hassegawa *et al.*, 2022). For example, although cotton is not a petroleum-based product, its poor environmental performance is a driver of novel wood-fibre based textiles (Hurmekoski *et al.*, 2018). These factors are expected to lead to an increase in production and demand for forest products, and therefore, industrial roundwood, by 2050 and beyond, as well as an emphasis on resource efficiency, which will drive increasingly diversified uses of wood biomass (Hurmekoski *et al.*, 2018).

3.3.3 Urbanization and demand for infrastructure

Urbanization and infrastructure development are leading to increased demand for biobased, mineral and metallic resources. For example, forest land is commonly exploited for activities such as mining and hydropower projects, and resources from these lands are used to construct buildings and transportation systems. This urban demand for resources may drive shifts in the availability and sourcing of forest products, particularly in regions experiencing rapid urban growth (Biłozor and Cieślak, 2021; Zucaro and Agostinho, 2025).

Much of the urbanization is expected to be concentrated in the emerging economies of Africa and Asia in the coming years (UN, 2024) – a shift that is also associated with higher living standards. Higher living standards are correlated with higher energy consumption and greater demand for commodities such as sanitary products, packaging and textiles (Biłozor and Cieślak, 2021; Ritchie *et al.*, 2024).

3.3.4 Shifts in wood energy use

Around half of all wood harvested globally is used as fuel – primarily for cooking and heating – though this figure has fallen from 60 percent in 1961 to about 50 percent in 2023 (FAO, 2024; FAOSTAT, 2025). This reliance on traditional woodfuel is particularly pronounced in emerging and developing economies (for instance, 60 percent of harvested wood in Asia and 90 percent in Africa is used as fuel) often on an unregulated basis (FAO, 2024; FAOSTAT, 2025). In fact, a recent study estimates annual woodfuel removals in Asia and Africa at 40 percent and 50 percent, respectively, higher than originally reported, while those for Europe and the Americas were estimated to be 20 percent and 10 percent, respectively, lower (Steel *et al.*, 2025). Although wood remains a central source of low-cost fuel, shifting socioeconomic factors and improved energy accessibility are expected to alter demand for traditional woodfuel, redirecting it towards other sources including fossil fuels and modern bioenergy systems (FAO, 2022b; Yayla *et al.*, 2025). The gradual but continued shift away from traditional woodfuel use could increase the availability of roundwood for engineered wood products (EWPs) and other wood products in the forest-based bioeconomy (Yayla *et al.,* 2025).

Simultaneously, the demand for renewable energy in high-income countries offers increased opportunities for wood-based bioenergy, complementing the broader shift towards low-carbon energy worldwide. Rising electricity demand, driven by factors such as rapid urbanization, digitalization, and electrification of transport, underscores the need for modern bioenergy technologies in tandem with other renewables (IEA, 2024). In contrast, in many developing regions, the focus is on transitioning from traditional woodfuels to cleaner cookstoves, more efficient charcoal production, and modern bioenergy products such as pellets or liquid biofuels (FAO, 2022b; IEA, 2024). Together, these trends highlight how evolving energy systems are reshaping the role of wood as a major fuel source across differing socioeconomic contexts.

3.3.5 Innovations in the forest sector

Innovation and technological advancements have the potential to significantly transform the value chains of wood-based industries. Additional value can be generated through product and process innovations, as well as by diversifying and integrating downstream value-added activities (Hurmekoski *et al.*, 2018; Hoeben *et al.*, 2023). For instance, advances in material science, particularly regarding the strength and uniformity of wood construction products, have opened new avenues for using EWPs as structural elements in buildings (Abed *et al.*, 2022; Tupėnaitė *et al.*, 2020). However, although the use of hardwood species for cross-laminated timber (CLT) (Hassler *et al.*, 2024) and glue-laminated timber (glulam) (Baño *et al.*, 2025) is technically feasible and actively explored in various world regions, their production is still associated with higher costs than when made from softwoods, partly because existing machinery is optimized for the processing of softwoods. In the paper industry, research and development have facilitated the production of novel specialty papers for packaging and sanitary applications, which are increasingly replacing the demand for traditional paper products (Hurmekoski *et al*., 2022).

Process optimization has made man-made cellulosic fibres (MMCFs) such as Lyocell and Tencel more sustainable alternatives to older lignocellulose-based textiles like viscose, potentially increasing their competition with cotton for market share, if production costs can be brought down (Felgueiras *et al.*, 2021; Hummel and Määttänen, 2024). Continued advancements in biorefinery technologies have been a primary driver of bioplastics expansion, as integrated systems deliver cost-competitive production, improved yields and greater efficiency alongside enhanced material performance (Jayakumar *et al.*, 2023; Pandey and Sharma, 2024). Modern biorefineries that enable the co-production of products like biofuels, biochemicals and bioplastics from pulp-based value chains have substantially expanded opportunities for value creation in wood-based industries (Hurmekoski *et al.*, 2018; Rajan *et al.*, 2024).

3.4 Key market trends of wood products

This section provides an overview of the main markets for forest products with a focus on recent developments and advances in research. Table 3.1 summarizes the market trends, drivers of demand, limitations to market growth, and trade-offs for five broad categories of forest products: (1) buildings and construction, (2) paper and packaging, (3) textiles, (4) energy and fuel, and (5) biochemicals and plastics. Particular attention is given to forest products used in the built environment. Further details on the other forest product groups are provided in the Appendix (Section 9.4). In addition, this section provides a regional perspective on forest product markets and demand trends.

Table 3.1 Market characteristics for five major wood product sectors

Building and construction	Forest products	Structural components (e.g. CLT, glulam) Non-structural components (e.g. LVL, MDF, OSB, particle board, plywood)
	Market trends	European Union (EU-27) leads production (92% of global CLT output and 68% of global glulam output in 2023) (FAOSTAT, 2025) North America and Asia-Pacific are rapidly scaling up manufacturing (Atkins *et al.*, 2023; FAOSTAT, 2025) Demand expected to increase significantly by 2030 (Nepal *et al.*, 2021)
	Megatrends affecting demand	Urbanization and demand for infrastructure (Verkerk *et al.*, 2022; Harte, 2017) Innovations and new technology (Abed *et al.*, 2022; Tupėnaitė *et al.*, 2023; Harte, 2017) Decarbonization and sustainability (FAO, 2022b; Hurmekoski *et al.*, 2018; Kumar *et al.*, 2024; Mallo and Espinoza, 2016)
	Limitations to market growth	Dependence on softwood supply (Pramreiter *et al.*, 2023b; Beck-O'Brien *et al.*, 2022) Slow regulatory adaptation (Brandt *et al.*, 2021; Firoozi *et al.*, 2024) High initial costs (Sorathiya, 2019; Gu *et al.*, 2020; Andersen *et al.*, 2023) Need for infrastructure and specialized labour (Verkerk *et al.*, 2022; Firoozi *et al.*, 2024) Market risk aversion (Hurmekoski *et al.*, 2018; Abed *et al.*, 2022)
	Trade-offs with other forest products	Increased EWP demand could reduce softwood availability for traditional markets, increase prices, and impact global trade. This is particularly true in areas where stand-alone sawmills or manufacturing plants are the industry norm (Nepal *et al.*, 2021) Residues could benefit bioenergy, pulp and biochemical industries (FAO, ITTO and United Nations, 2020; Saal *et al.*, 2017; Churkina *et al.*, 2020) The tendency towards integrated models of production (e.g. sawmill + EWP manufacturing within the same unit) allows for more efficient cascading of product types and diversified revenues, which alleviates some of the demand tensions between forest products (Jonsson *et al.*, 2021; Hurmekoski *et al.*, 2018) Additionally, the growing market demand and the fragile nature of transport economies of scale for EWP have made manufacturing hubs designed to supply regional market demand for EWP increasingly competitive. As a result, investors are showing interest in funding new production facilities in non-traditional production regions, such as the emerging CLT factories in Spain (Basque Country and Catalonia) and in Portugal
Paper and packaging	Forest products	Graphic paper Newsprints Sanitary paper Wrapping and packaging papers
	Market trends	China and the United States are the top producers of paper and paperboard (48% of global production in 2023) (FAOSTAT, 2024) Projected decline in graphic paper and newsprint demand (FAOSTAT, 2024; Johnston, 2016) Demand for packaging materials and sanitary products has increased resulting in an overall increase in pulp consumption (FAOSTAT, 2024; Hurmekoski *et al.*, 2022)
	Megatrends affecting demand	Digitalization (Johnston, 2016; Verkerk *et al.*, 2022; UNECE and FAO, 2024) Decarbonization and sustainability (Hurmekoski *et al.*, 2018; Thapliyal *et al.*, 2024)

	Limitations to market growth	Digitalization, global internet adoption and shifts to electronic communications (Johnston, 2016) Rising energy costs (Furszyfer Del Rio *et al.*, 2022; UNECE and FAO, 2024) Limits in feedstock supply due to rising regulatory compliance and standards (Beck-O'Brien *et al.*, 2022; Rajan *et al.*, 2024; European Commission, 2021)
	Trade-offs with other forest products	Increased demand for other products (e.g. bioplastics, biotextiles, biochemicals) that also rely on feedstock used for paper production (Hurmekoski *et al.*, 2018; Rajan *et al.*, 2024) In forests where there is competing demand from EWP within traditional paper and pulp markets, the quality of timber available for EWPs is lower, affecting quality, strength and production capacity of CLT output (FAO, 2024)
Textiles	Forest products	Man-made cellulosic fibres (MMCFs) (e.g. viscose, acetate, Lyocell, modal, cupro)
	Market trends	Asia-Pacific dominates global MMCF production (Dharwadkar and Hautamäki, 2024; Hummel and Määttänen, 2024) North America is a major producer and supplier of dissolving pulp (Dharwadkar and Hautamäki, 2024; Hummel and Määttänen, 2024) MMCF production capacity is projected to increase by 2035 (Dharwadkar and Hautamäki, 2024; Hummel and Määttänen, 2024; Textile Exchange, 2024)
	Megatrends affecting demand	Decarbonization and sustainability (Dharwadkar and Hautamäki, 2024) Innovations and new technology (Edgar and Zhang, 2020; Felgueiras *et al.*, 2021)
	Limitations to market growth	Lack of regulatory approval for large-scale use of alternative solvents (Orfanidou *et al.*, 2023) Challenges in overhauling textile supply chains and manufacturing operations (Kallio, 2021) More expensive than conventional textiles (e.g. cotton and synthetics) (Orfanidou *et al.*, 2023)
	Trade-offs with other forest products	Increased wood-based textiles creates additional demand for by-products such as sawmill chips, thus benefiting vertically integrated solid wood product manufacturers (Kallio, 2021) Additional MMCF production could reduce investment and capacity of other wood products that use the same feedstock (e.g. panels, paper pulp) (Kallio, 2021) MMCFs can be produced from both coniferous and non-coniferous feedstocks, reducing competition for coniferous wood resources (Morland and Schier, 2020) Reduction in paper production could feed into the expansion of MMCF production capacity due to conversion of paper pulp mills (Beck-O'Brien *et al.*, 2022; Kallio, 2021)
Energy and fuel	Forest products	Biofuels Sustainable aviation fuels Traditional woodfuel Wood pellets
	Market trends	Woodfuel dominates harvested wood use in several regions, as much as 60% in Asia and 90% in Africa (FAOSTAT, 2024; FAO, 2024). With new estimation procedures ongoing, these values may be revised upward in many world regions (Steel *et al.*, 2025) Global wood pellet production has increased rapidly, by more than 50 million tonnes between 2000 and 2018 (Rodriguez, 2022; Saletnik *et al.*, 2022; FAOSTAT, 2024) Almost half of global wood pellet production was in Europe in 2023 (FAOSTAT, 2024; IEA, 2024) Demand for bioenergy is expected to grow, especially in Brazil, China, Europe, India and the United States (IEA, 2024)

	Megatrends affecting demand	Urbanization and demand for infrastructure (IEA, 2024; FAO, 2022b; Al Mubarak *et al.*, 2024) Shifts in energy use (FAOSTAT, 2024; FAO, 2024; FAO, 2022b; IEA, 2024) Innovations and new technology (IEA, 2017; FAO, 2022b; Vardon *et al.*, 2022; Saletnik *et al.*, 2022) Decarbonization and sustainability (Bailis *et al.*, 2015; Antar *et al.*, 2021)
	Limitations to market growth	Sustainability issues (e.g. deforestation, soil erosion, ecosystem damage) if traditional woodfuel usage is not managed (Al Mubarak *et al.*, 2024; Antar *et al.*, 2021) Cost competitiveness compared with conventional fossil fuels (Al Mubarak *et al.*, 2024; Zhang *et al.*, 2013)
	Trade-offs with other forest products	Competing use of roundwood for woodfuel and for industrial roundwood (Beck-O'Brien *et al.*, 2022; FAO, 2022b) Competing use of forest harvest residues and industrial wood manufacturing residues as biofuel versus feedstock for bioenergy products (e.g. wood pellets, sustainable aviation fuel) (Calvin *et al.*, 2021) or wood fibre insulation in buildings (O'Brien *et al.*, 2025; Siciliano *et al.*, 2023)
Biochemicals and bioplastics	Forest products	Adhesives Agricultural input (e.g. fertilizers) Coatings Packaging Pharmaceuticals Solvents
	Market trends	Relatively small sector (e.g. bioplastics account for 0.7% of global plastic production) (Plastics Europe, 2024; European BioPlastics, 2024) High degree of variation in terms of projected growth in production (e.g. 26–113 million tonnes of biochemical production by 2050) (IEA Bioenergy, 2020)
	Megatrends affecting demand	Decarbonization and sustainability (Panchaksharam *et al.*, 2019; Jayakumar *et al.*, 2023; Gaffey *et al.*, 2021) Innovations and new technology (Pandey and Sharma, 2024; Jayakumar *et al.*, 2023)
	Limitations to market growth	Limited and fluctuating feedstock availability (Panchaksharam *et al.*, 2019; Rajan *et al.*, 2024) High costs in scaling up (Hurmekoski *et al.*, 2018; IEA Bioenergy, 2020) Conflicting sustainability benefits (Ögmundarson *et al.*, 2020) Inconsistent regulatory environment for market development, capital allocation and product standards (Rajan *et al.*, 2024; Panchaksharam *et al.*, 2019)
	Trade-offs with other forest products	Competing feedstock with other products (e.g. bioenergy and textiles) (Rajan *et al.*, 2024; Hurmekoski *et al.*, 2018)

Notes: CLT = cross-laminated timber; EWP = engineered wood product; glulam = glue-laminated timber; LVL = laminated veneer lumber; MDF = medium-density fibreboard; MMCF = man-made cellulosic fibre; OSB = oriented strandboard

Source: Authors' own elaboration.

3.5 Regional[8] trends and developments

3.5.1 Europe and North America

Europe and North America lead the world in wood production and exports (Egenolf *et al.*, 2022). In 2023, both regions produced almost 55 percent of global industrial roundwood and 61 percent of global sawnwood (FAOSTAT, 2025). In 2023, Europe harvested about 753 million m^3 of wood (FAOSTAT, 2025), and has well-developed capacities for sawmilling, pulp and paper production, and bioenergy (Bozzolan *et al.*, 2024). According to FAOSTAT (2025), North America harvested 543 million m^3 of roundwood in 2023. Within the European Union (EU-27), industrial capacity is particularly high in countries such as Finland, Germany and Sweden.

Europe and North America are the largest suppliers of EWPs for construction at the global scale, with the European Union (EU-27) accounting for about 92 percent of global CLT production, and 68 percent of global glulam production, while the United States produces almost 46 percent of global laminated veneer lumber (LVL) (FAOSTAT, 2025). Both regions are also responsible for a large share (54 percent) of global pulp production, although increased digitalization could reshape the wood pulp market and use of pulp feedstock (e.g. more pulp being diverted towards novel and value-added wood-based products; Johnston, 2016).

In recent years, sawnwood production, imports, and use in Europe and North America have been affected by the war in Ukraine, a slowing down of regional economies after the COVID-19 pandemic, and a fall in building construction and renovation rates (UNECE and FAO, 2022, 2021a). Nevertheless, overall demand for industrial roundwood is expected to increase within Europe, potentially resulting in a decline in net exports. North America is expected to follow a similar trend, albeit at a slower growth rate. Both regions are expected to remain net exporters of sawnwood after 2030 (UNECE and FAO, 2022).

3.5.2 Asia-Pacific

Forest industries in Asia have grown significantly in the last 50 years, driven by access to cheap timber, land conversion policies and the increased demand for wood products due to population growth (Lauri *et al.*, 2021). Asia contributes 29 percent of the world's roundwood production but is a net importer of most wood products. Eastern Asia[9] is the biggest importer of pulp for paper production in the Asia-Pacific region and, at the same time, also produces 39 percent of global paper and paperboard (FAO, 2024; FAOSTAT, 2025). Furthermore, China is a major importer of solid wood products, woodchips, and wood pulp, due to a ban on commercial logging of natural forests which began in 2017 and created a gap in domestic supply and demand of wood products (Wang *et al.*, 2023).

Southeast Asia[10] is a net exporter of sawnwood, paper and paperboard, and pulp for paper. Similarly, Oceania is a net exporter of most wood products except for paper and paperboard, with Australia and New Zealand being the largest contributors to the production and export of these products (FAOSTAT, 2025).

There have also been significant shifts away from the direct use of wood as fuel in East and Southeast Asia, with similar declines expected in South Asia, indicating a transition towards cleaner sources of energy that could be supplemented by renewable forest biomass products. Australia, China, India, Indonesia and Thailand are now significant producers of biofuels such as ethanol and biodiesel derived from agricultural biomass (FAO, 2019).

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8 Regions defined as in literature cited.
9 Includes China, the Democratic People's Republic of Korea, Japan and the Republic of Korea.
10 Includes countries with extensive forested area like Brunei Darussalam, Indonesia, Malaysia and Viet Nam.

3.5.3 Africa

According to 2022 data, the African region produced 3.9 percent of the world's industrial roundwood, with East and West African countries contributing the largest share. Only 5 percent of this volume was exported. With paper and paperboard, for example, the African region produced less than 0.8 percent of the global production volume in 2023, with most of the production originating in South Africa (FAOSTAT, 2025). Indeed, several analyses of the African forest sector point towards the historical trade imbalances between export of primary wood products and the import of higher-value secondary and tertiary products (ANRC, 2021; FAO and Dalberg Catalyst, 2024).

One of the major reasons for low value creation in the African forest sector is the extensive use of wood as fuel for heating and cooking. Around 90 percent of wood harvested in Africa is consumed domestically as woodfuel for heating and cooking (FAO, 2025). Annual woodfuel consumption in Africa already exceeds 600 million m^3 and is a major driver of forest degradation (Indufor Oy and Criterion Africa Partners, 2017).

Another cause for low value creation in several African countries is that their forest sectors are often structured around the export of low-value primary forest products such as unprocessed roundwood, rather than value-added secondary and tertiary products such as sawnwood, furniture, and paper and packaging (FAO and Dalberg Catalyst, 2024). In the southern African region, due largely to investments into plantations, South Africa and the United Republic of Tanzania (Andrew, 2022) were the only countries with positive trade balances for processed wood products such as case materials, wrapping papers and newsprint. All other countries in the southern region, such as the Democratic Republic of the Congo, Lesotho, Madagascar and Malawi, recorded negative trade balances despite the forest sector contributing strongly to their respective national gross domestic products (GDPs) (ANRC, 2021).

Moreover, Africa's population is expected to almost double to 2.08 billion people in 2040, while current United Nations projections indicate that Africa's cities will grow by an additional 900 million people until 2050 (OECD, UN ECA and AfDB, 2022). This population growth and rapid urbanization is increasing access to services, infrastructure and economic growth for hundreds of millions of people, which in turn increases demand for energy, food, raw materials, consumer goods and digital infrastructure. As a result, food security, biofuels and energy production are likely to be the cornerstones of the African bioeconomy with urbanization, population growth, income growth, shifts in energy use and digitalization being key drivers of the transition (Fletcher *et al.*, 2017; Malabo Montpellier Panel, 2022).

3.5.4 Latin America and the Caribbean

The Latin America and the Caribbean (LAC) region produced almost 15 percent of global industrial roundwood supply in 2023 (FAOSTAT, 2025). This figure has risen from 3 percent in 1960, and at a rate much faster than other emerging economies. The change can be attributed to increased harvesting in Brazil, which now accounts for almost two-thirds of all wood produced in South America, and the expansion of timber plantations in Chile and Uruguay (Ardila *et al.*, 2021; Morales Olmos, 2022).

Moreover, the LAC region produced 7.5 percent of global sawnwood in 2023 and is a leader in pulp production and biofuels (FAOSTAT, 2025; IEA, 2023; Lima, 2025). In recent years, the pulpwood industry has expanded rapidly, with the region producing 18 percent of global wood pulp in 2023 (FAOSTAT, 2025). In terms of trade, China has emerged as the largest importer of South American wood products, accounting for about 30 percent of the value of exports in 2021. Europe and the United States are also major destinations for

Latin American forest products; however, 18 percent of Latin American exports are imported by countries elsewhere in Latin America (Ardila *et al.*, 2021; Morales Olmos, 2022).

The forest industries in South America have grown significantly in the last 50 years, driven by population growth and the increased demand for wood products (Lauri *et al.*, 2021). In addition to these demand-driven factors, supply-side investments, such as Chile's large-scale plantation expansions, are critical in enabling robust industry growth and shaping forest products trade outcomes (Raga, 2009). Argentina, Brazil, Chile and Uruguay, with the largest forest-based industries in the region, have all shifted towards the use of sustainable bioderived fuels such as ethanol from bagasse production, biodiesel from soy residues, black liquor from pulpwood production, and wood-processing wastes (Ardila *et al.*, 2021; Siegel *et al.*, 2022).

3.6 Knowledge gaps/uncertainties shaping forest-based bioeconomy trends

The literature points to a wide range of drivers that will shape the future supply and demand of wood products. However, across these drivers, major uncertainties remain that warrant closer attention in the context of forest-based bioeconomy development. These uncertainties span multiple knowledge areas, reflecting data limitations, methodological differences, and divergent assumptions about future market and regional trends. These uncertainties need to be considered carefully when assessing pathways for forest-based bioeconomy development, as they affect both the robustness of projections and the design of policies. Consequently, forecasts should be interpreted as best estimates given current conditions, with decision-making processes accounting for a fairly wide range of potential future trajectories. Recognizing these knowledge gaps is essential for building more robust projections of wood product markets and for designing policies that support sustainable forest-based bioeconomies.

3.6.1 Market demand fluctuations

A major source of uncertainty lies in forecasting how global economic trends, consumer preferences and evolving policy frameworks will affect the long-term demand for wood products. For instance, the future uptake of EWPs or biobased alternatives to plastics and textiles is highly dependent on cost competitiveness, regulation and public acceptance – factors that are difficult to predict (Verkerk *et al.*, 2022). These uncertainties highlight the need for flexible modelling approaches that can incorporate disruptive changes and assess the resilience of wood product markets under different adoption pathways. Some of those disruptive changes are investigated in Chapter 4, where the role of EWP in building construction is analysed as a case study to illustrate how emerging end uses can alter wood product markets.

3.6.2 Global supply chains

Supply projections are complicated by uneven forest resources (e.g. shortages in some softwood supplies contrasting with relatively abundant hardwood resources [Bozzolan *et al.*, 2024]), differences in wood quality, regional management capacities, and the concentration of production in a limited number of countries. The extent to which planted forests can expand, productivity can be improved, or residuals can be mobilized remains uncertain. Moreover, smallholder contributions are often underreported in official statistics, obscuring their role in global supply (Midgley *et al.*, 2017). Policy changes such as stricter sustainability regulations or trade restrictions add another layer of unpredictability. These uncertainties suggest that global supply–demand models must better integrate regional disparities, governance frameworks and informal market dynamics to produce more reliable scenarios.

3.6.3 Unsustainable use and competing land demands

A persistent uncertainty is how competing pressures on land – particularly agriculture and woodfuel – will affect the long-term availability of timber (FAO, 2025). While global models assume sustainable harvest levels, evidence shows that over-exploitation is common in some regions (Zhang *et al.*, 2021), especially where agricultural expansion remains the main driver of forest loss (FAO, 2022c). The critical uncertainty lies in whether future policies and land-use strategies will effectively balance food, energy and timber needs without accelerating deforestation. Modelling research is needed on integrated land-use planning approaches that explicitly account for these competing pressures within bioeconomy strategies.

3.6.4 Smallholder forestry systems

Smallholders account for a substantial share of global plantation areas, particularly in emerging economies, yet their role in supply remains poorly captured in most projections. Uncertainties stem from data gaps, the informal nature of many smallholder operations, and variations in land tenure systems across regions (Verdone, 2018). At the same time, smallholders are likely to play a growing role in meeting local demand where industrial plantations face spatial or economic limits (Ota *et al.*, 2022). Better data and policy attention to smallholder systems are essential to capture their potential contributions, as well as the risks of exclusion or unsustainable practices if they remain unsupported.

3.6.5 Climate change impacts

Climate change is one of the largest sources of uncertainty for forest supply from both natural and planted forests, affecting growth, mortality and disturbance regimes. While some regions may experience productivity gains, others face increasing risks of drought, fire or pests, with potentially severe consequences for timber supply (Altman *et al.*, 2024). The scale and direction of these impacts remain highly uncertain, as do the adaptive responses of forest managers and policymakers. Projections that ignore these risks may significantly overestimate supply. More research is needed to integrate climate impacts and adaptation strategies into forest sector modelling to better guide bioeconomy development.

Chapter 4 enhances this understanding by integrating climate-related variables into its projections.

3.6.6 Substitution effects and carbon storage

A final area of uncertainty emerging from this literature review concerns the climate benefits of expanding wood use in the built environment. Estimates of substitution and storage effects vary widely depending on system boundaries, assumptions about forest management, and alternative materials considered. These methodological differences generate diverging narratives about the role of wood products in global climate change mitigation. Addressing these uncertainties requires transparent accounting frameworks and comparative studies across modelling approaches, to clarify the conditions under which EWPs can most effectively contribute to emission reductions. Chapter 5 explores these issues in further detail, including a preliminary analysis of the carbon storage and material substitution effects (e.g. replacing steel or concrete with EWPs) to assess the overall carbon mitigation potential of expanded use of EWPs.

4 Scenario projections of changes in demand of engineered wood products

This chapter presents modelling results[11] that quantify the potential impacts of engineered wood product (EWP) adoption in residential building construction on global forest product markets. The modelling analysis uses the FOrest Resource Outlook Model (FOROM) and analytical framework described in Section 2.2 to project specific market outcomes through 2070, and extending beyond the business-as-usual (BAU) demand scenarios examined in Section 4.1. Impacts of changes in the forest sector on the broader economy or dynamic pricing are not captured through FOROM's partial equilibrium modelling approach. Specifically, the projections shown in this chapter represent how the demand for wood products in residential building construction may increase substantially above what historical patterns and future income levels may suggest. To do so, shifts in urbanization, construction practices and material usage are combined with population growth, which may contribute to increased demand for wood products in building construction, potentially beyond what traditional models based on gross domestic product (GDP) growth alone could predict.

4.1 Business-as-usual scenario and demand for engineered wood products

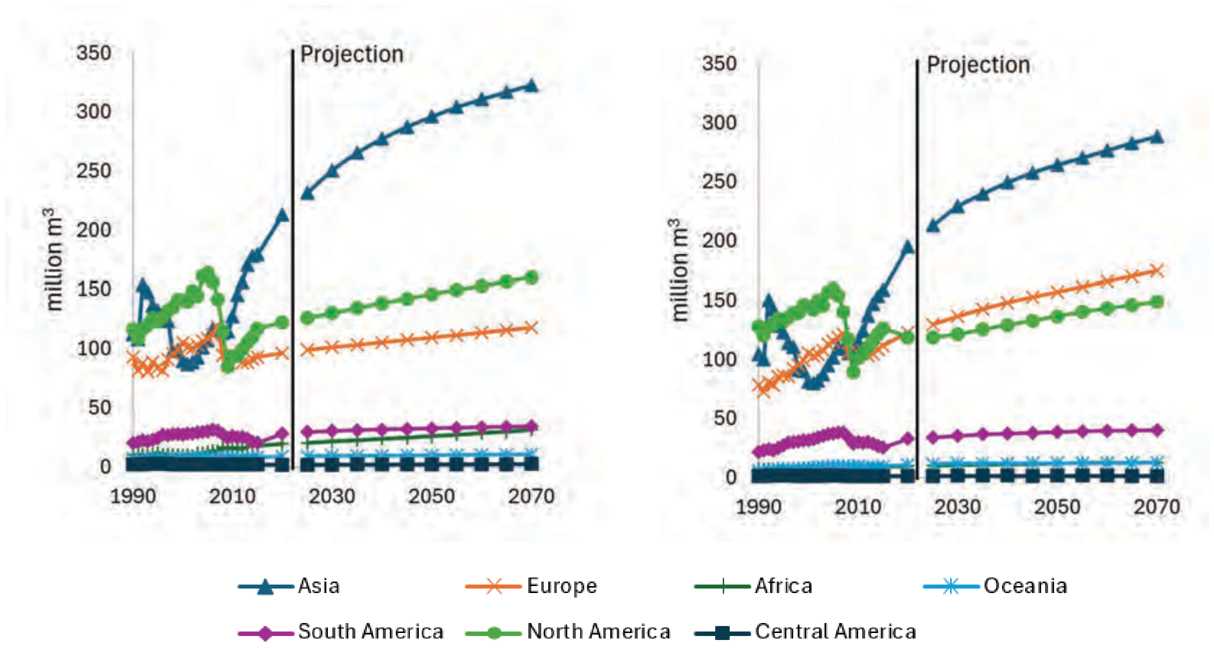
The BAU scenario projections depicted in Figures 4.1 and 4.2 indicate that without considering additional shifts in EWP demand – such as adoption of new construction technologies or significant changes in material preferences – the demand for sawnwood and industrial roundwood will largely follow historical patterns. In this scenario, the growing demand of these materials is primarily driven by growth in economic activity and population, particularly in Asia and Africa.

For sawnwood and industrial roundwood, Figures 4.1 and 4.2 show that demand and production in the BAU scenario generally increase over time, particularly in Asia, which continues to see the highest levels of both demand and supply growth. In contrast, Europe and North America are projected to exhibit modest growth, reflecting lower or stagnating population growth and demand for these materials due to mature markets and alternative construction practices. Africa and South America, on the other hand, show stable demand and production trends.

[11] All results in this chapter refer to FOROM modelling regions (see Table A2 and Table A3), which are not the same as political or current FAO data regions.

Figure 4.1 Historical and projected sawnwood demand and production in the business-as-usual scenario by region, 1990–2070, assuming no increase in engineered wood product demand

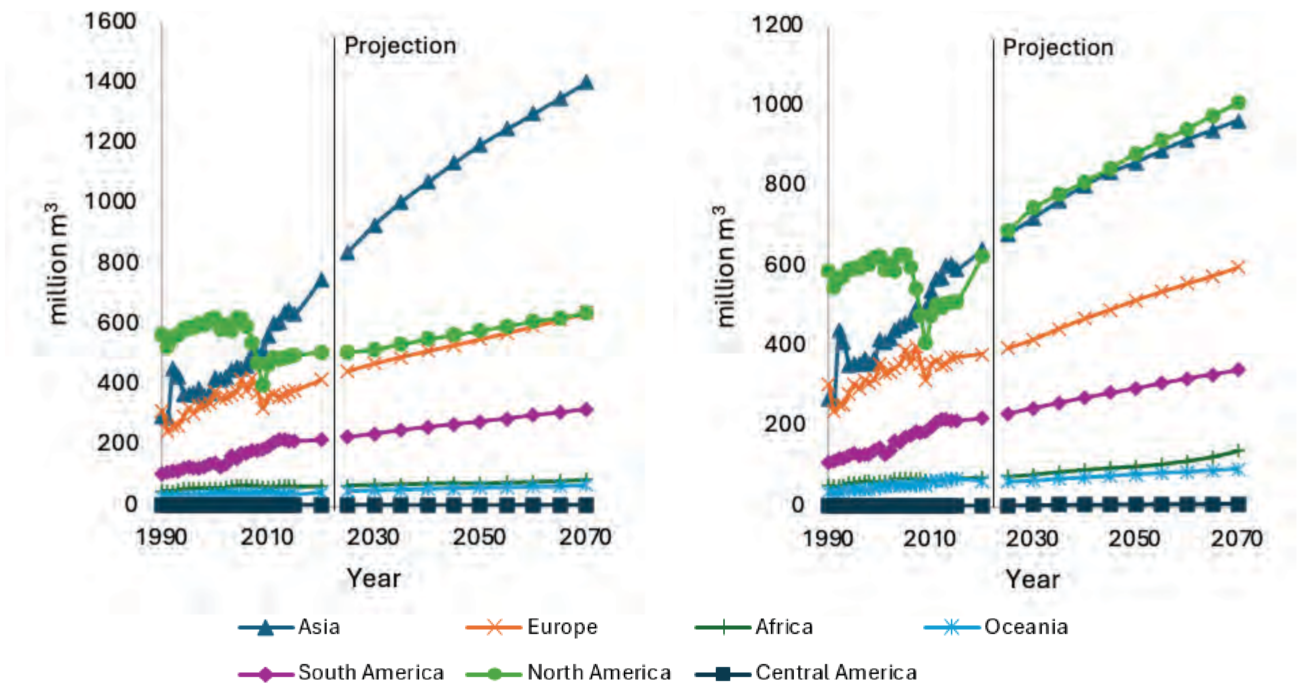
(a) Demand (b) Production



Notes: Historical data from 1990 to 2015 (FAOSTAT, 2025); projected from 2020 to 2070. The decline in Asia in the 1990s was driven by the Japanese recession, while the decline in North America, Europe and South America in 2008/09 was driven by the global financial crisis.
Source: Authors' own elaboration.

Figure 4.2 Historical and projected industrial roundwood demand and production in the business-as-usual scenario by region, 1990–2070, assuming no increase in engineered wood product demand

(a) Demand (b) Production

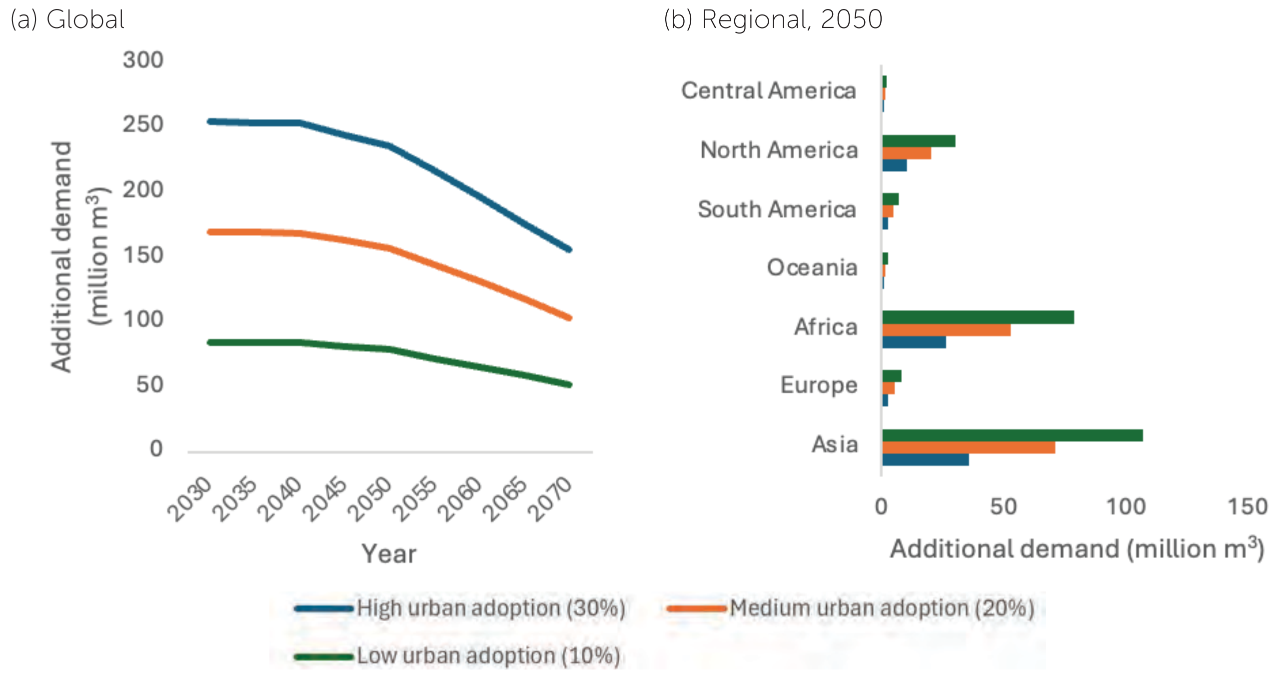


Notes: Historical data from 1990 to 2015 (FAOSTAT, 2025). Projected from 2020 to 2070. *Source*: Authors' own elaboration.

Varying rates of additional wood material usage in urban building construction can significantly elevate the demand for EWPs beyond what is projected in the BAU scenario (Figures 4.3 and 4.4). Figure 4.3a shows how increased urban adoption rates for residential buildings directly affect the demand for EWPs in building construction by around 50 to 250 million m^3 in any given year. This reflects a growing trend in the construction sector towards more sustainable and environmentally friendly building materials. The trend is decreasing over time, as Figure 4.3a depicts additional demand for EWPs. Every year, additional demand is occurring, but at a slower pace over time, reflective of slowing urbanization rates. Figure 4.3b emphasizes important regional heterogeneity in additional demand of EWPs for building construction, primarily driven by higher urbanization in Africa and Asia, relative to other regions.

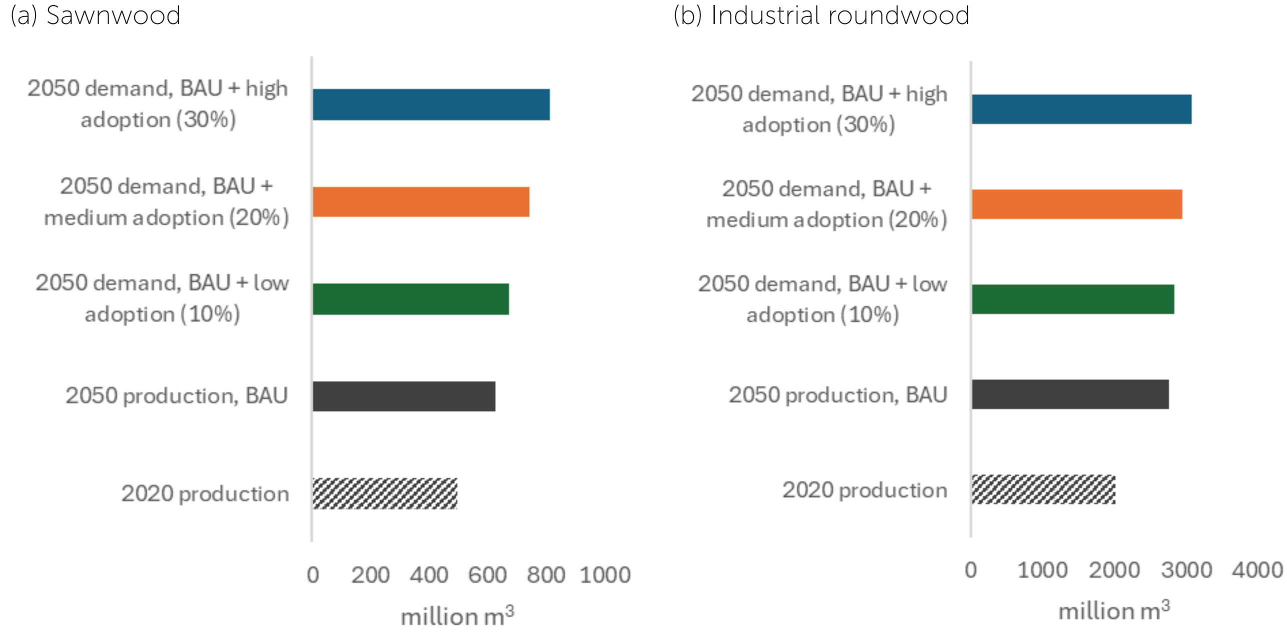
Figure 4.4 complements this by showing historical production and projected demand trends for sawnwood and industrial roundwood across different urban adoption scenarios. Demand of sawnwood and industrial roundwood in 2020 is around 0.5 and 2.0 billion m^3, respectively. Here, demand levels are projected to rise more sharply under higher urban adoption rates, particularly in regions undergoing rapid urbanization. By 2050, the demand of sawnwood and industrial roundwood could reach levels as high as 0.8 and 3.1 billion m^3, respectively. In these regions, the increased use of wood-based materials for building construction drives up both sawnwood and industrial roundwood demand beyond the production trajectories laid out in the BAU scenario.

Figure 4.3 Global and regional projected additional demand of engineered wood products from increased urban adoption rates when compared with the business-as-usual scenario, 2030–2070



Notes: Figure 4.3a shows the additional demand from 2030 to 2070. Figure 4.3b shows a snapshot in time of where that demand is regionally in 2050.
Source: Authors' own elaboration.

Figure 4.4 Global historical and projected sawnwood and industrial roundwood demand across urban adoption scenarios



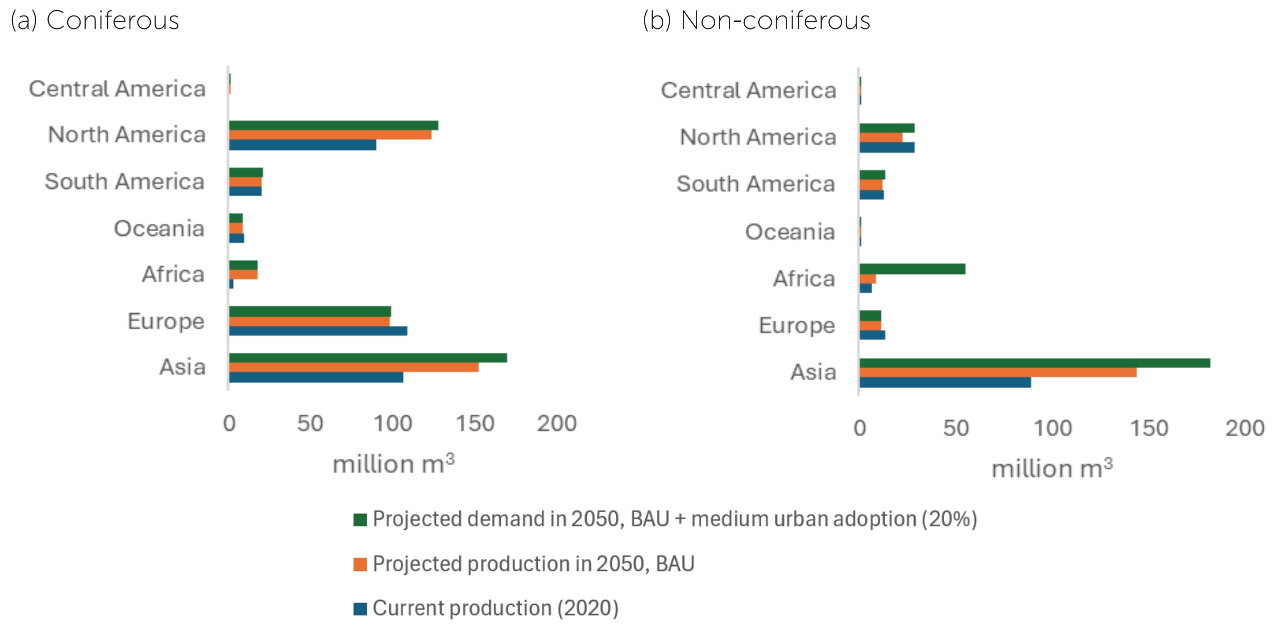
Note: BAU = business-as-usual.
Source: Authors' own elaboration.

Together, the data presented in Figures 4.3 and 4.4 illustrate how urban adoption rates for residential buildings affect the equilibrium between global demand and production of wood products. In these models, global demand must equal global production, so increases in demand directly imply the need for corresponding increases in output. Under the BAU scenario, production – and therefore demand – rises gradually by 2050, reflecting traditional growth drivers without major shifts in construction practices. However, when higher urban adoption rates are considered, demand for EWPs accelerates, pushing total wood demand well above the BAU production trajectory. The key comparison is between 2050 demand under the EWP scenarios and 2050 BAU production: the gap between them represents the additional production that would be required to satisfy future demand. For instance, the difference between the blue and black bars in Figure 4.4a highlights this potential imbalance.

4.2 Regional variation in demand and production of engineered wood products

The results in this subsection focus on the baseline scenario that assumes a medium level of urban adoption, floor area rate, and wood use intensity. Figures 4.5–4.8 provide a view of global trends in sawnwood and industrial roundwood production and demand, with a focus on how the different FOROM modelling regions (see Table A2 and Table A3) are projected to experience supply–demand imbalances. By comparing historical and projected data across various scenarios, these charts reveal regions where production may outstrip demand and areas where production will fall short, creating pressures on external markets to meet demand.

Figure 4.5 Current and projected sawnwood production in the business-as-usual scenario, and projected demand in the medium urban adoption scenario, by region

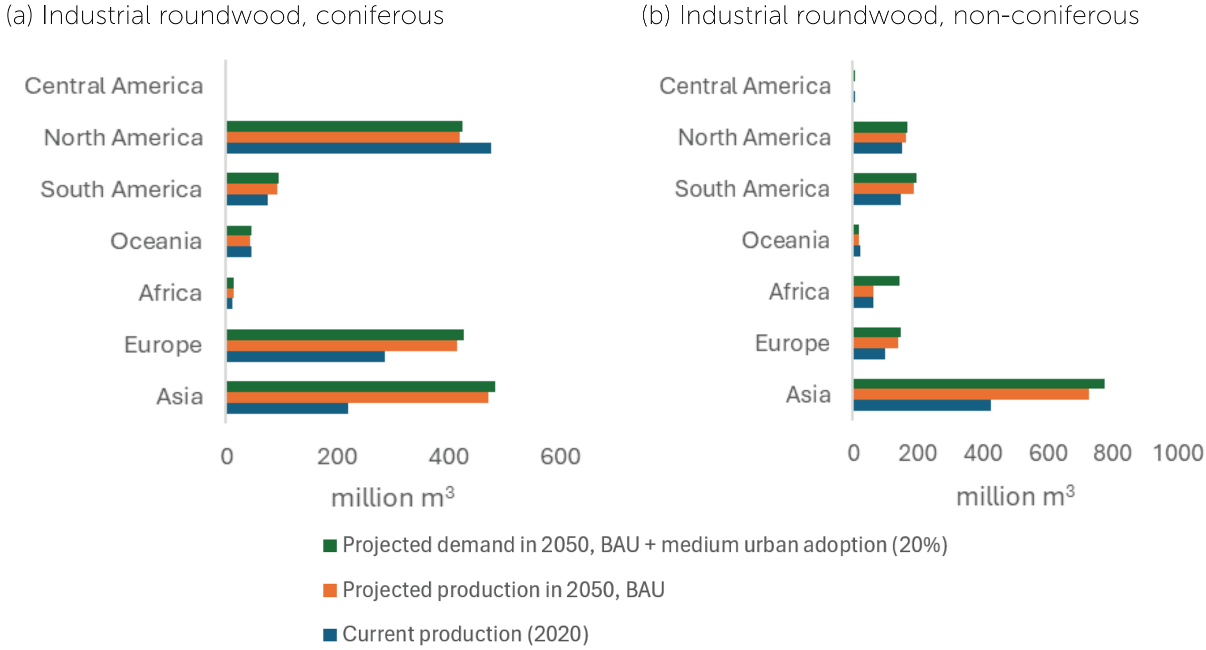


Note: BAU = business-as-usual.
Source: Authors' own elaboration.

Figure 4.5 presents scenario results generated by the FOrest Resource Outlook Model (FOROM). Specifically, it compares projected sawnwood production under the BAU scenario with projected demand under the medium urban adoption scenario, by region. This representation highlights how the equilibrium between production and consumption could evolve under different drivers of demand. While the figure focuses on BAU production levels to provide a consistent benchmark, it should be noted that FOROM does project modest increases in production capacity in several regions by 2050. Nonetheless, these increases generally remain insufficient to match the faster growth in demand implied by higher urban adoption rates. For example, Asia remains the largest producer, but its domestic output is unlikely to keep pace with rapidly rising demand, particularly as EWP use expands in urban construction. North America and Europe, with mature markets and relatively stable production trajectories, are expected to experience limited shortfalls but will not fully offset the global demand surge. In contrast, regions such as Africa and South America may face widening gaps between demand and local production, potentially leading to increased interregional trade.

Similarly, the projected production and demand for industrial roundwood by region shows a comparable imbalance (Figure 4.6). Industrial roundwood serves as the primary input for sawnwood production, which in turn is used to manufacture EWPs. Asia is expected to continue dominating non-coniferous industrial roundwood production; however, demand in rapidly growing economies such as China and India may strain local supplies, leading to greater dependence on imports. In Africa and South America, rising industrial roundwood demand – driven by both traditional uses and the growing production of sawnwood and EWPs – may exceed existing production capacities, underscoring the need for investment in sustainable forest resources and processing infrastructure.

Figure 4.6 Current and projected industrial roundwood production in the business-as-usual scenario, and projected demand in the medium urban adoption scenario, by region

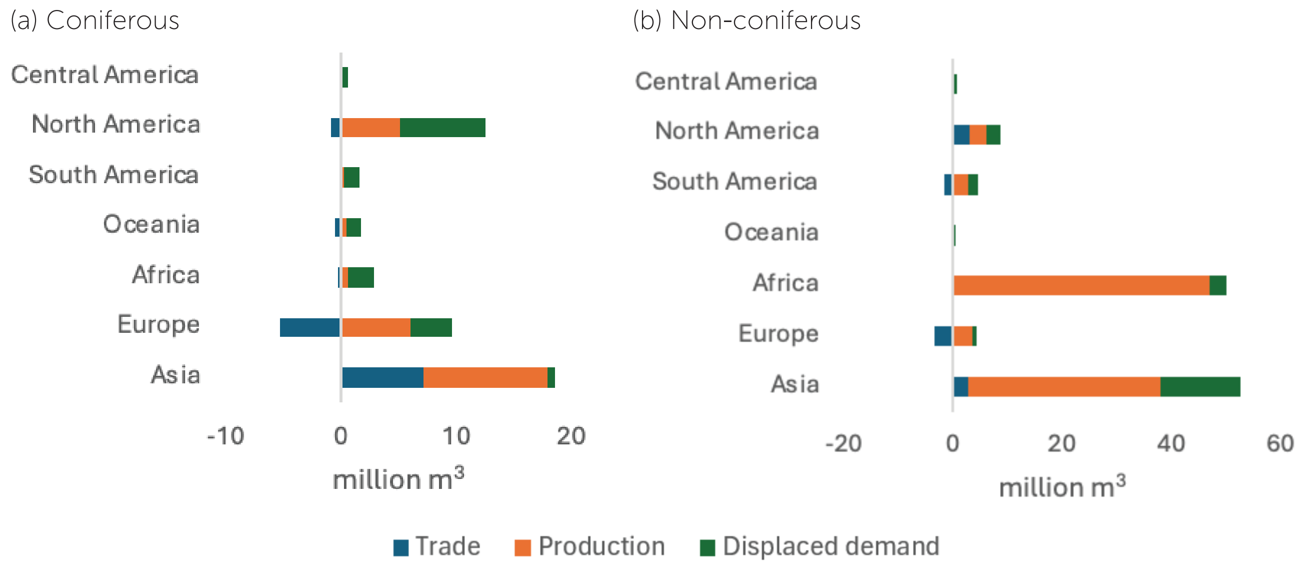


Note: BAU = business-as-usual.
Source: Authors' own elaboration.

Figures 4.7 and 4.8 show how increased demand for sawnwood and industrial roundwood is met by region in 2050 under a medium urban adoption (20 percent) scenario versus BAU, shedding further light on the potential challenges regions may face in meeting increased demand based on increased urban adoption. For sawnwood (Figure 4.7), the medium urban adoption scenario highlights a marked increase in demand in regions like Asia, which already faces significant pressure on its production capacity. Under this scenario, production from Asia is expected to fall short as indicated by a positive value for trade, or an increase in imports to meet demand. Imports would most likely originate from North America, Europe, and potentially South America where a negative trade indicates excess production not needed to meet demand. While North America and Europe are able to meet much of the demand within their own borders, they may still face external pressure to export sawnwood, which could lead to tight market conditions.

Similarly, for industrial roundwood (Figure 4.8), the medium urban adoption scenario shows that some of the modelling regions (Table A2 and Table A3) will continue to see growing demand including Asia, Africa and North America. Production is projected to grow in Asia, for example, with the expansion of urban areas and a shift towards using more engineered wood materials in construction. As a result, they are predicted to have increased demand for non-coniferous roundwood that can be met primarily through excess production, and to a lesser extent increased imports. Europe may provide additional roundwood to meet the increasing global demand. North America is predicted to have a continued reliance on imported wood to meet demand. This scenario emphasizes the global nature of forest product supply chains, where imbalances in production will likely lead to increased trade flows between regions, potentially from Africa to North America and Asia.

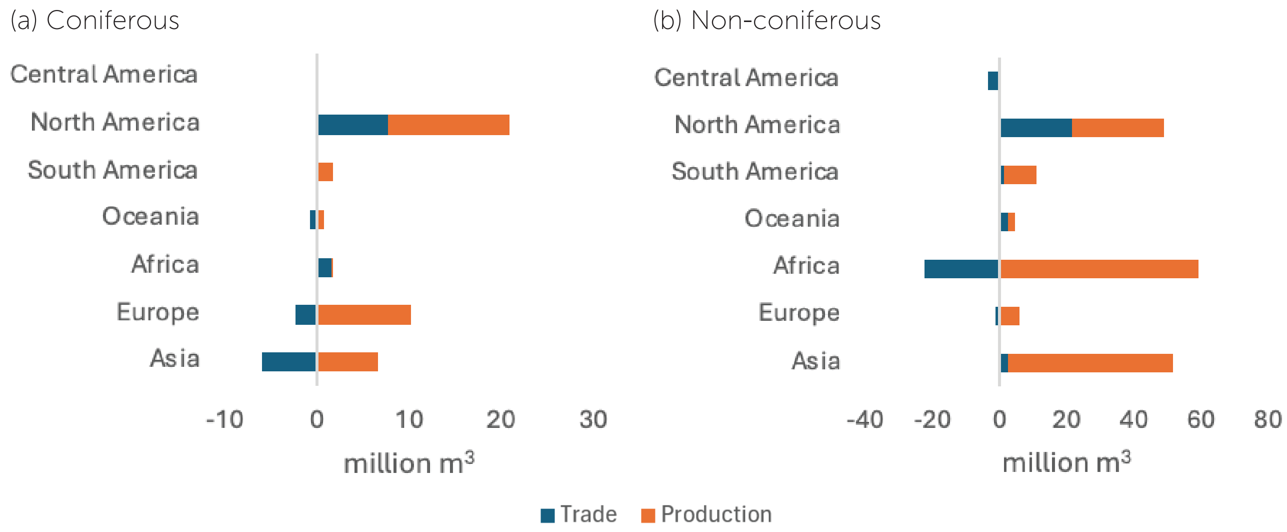
Figure 4.7 How change in demand of sawnwood is met by region, 2050, medium urban adoption scenario versus business-as-usual scenario



Notes: Displaced demand is the amount of sawnwood used as an input in manufacturing engineered wood products that otherwise was projected to be used ("consumed") as a final product (e.g. lumber) in the business-as-usual scenario. Trade is calculated as the difference between imports and exports to reflect how trade can be used to meet increased demand for manufacturing engineered wood products. Negative values for trade suggest imports minus exports are lower than under the business-as-usual scenario. This could occur by decreasing imports and/or increasing exports.
Source: Authors' own elaboration.

Figures 4.7 and 4.8 collectively show a clear pattern: Asia and Africa are expected to face substantial demand increases for both sawnwood and industrial roundwood. In Africa, production of non-coniferous sawnwood could be expected to ramp up significantly to meet the increased demand but their ability to do this will depend on substantial investments in milling and manufacturing capacity as current production is low (Figures 4.1b, 4.2b). North America and Europe will likely play a role in meeting global shortfalls, although they may also face increased domestic demand which could limit their export capabilities. These dynamics suggest a shifting global market where trade flows will become increasingly important, and regions will need to collaborate to ensure adequate supply to meet the rising demand for EWPs in construction.

Figure 4.8 How change in demand of industrial roundwood is met by region, 2050, medium urban adoption scenario versus business-as-usual scenario



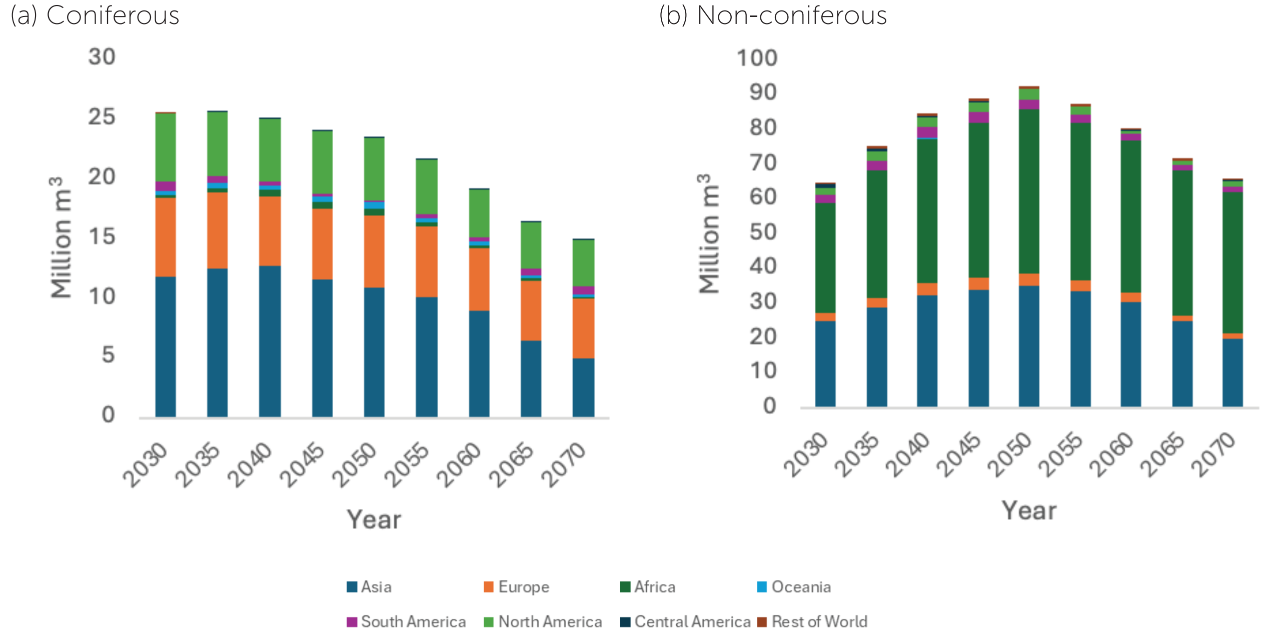
Notes: Trade is calculated as the difference between imports and exports to reflect how trade can be used to meet increased demand for manufacturing engineered wood products. Negative values for trade suggest imports minus exports are lower than under the business-as-usual scenario. This could occur by decreasing imports and/or increasing exports.

Source: Authors' own elaboration.

Figures 4.9–4.12 provide a view of the evolving dynamics of wood product production, demand and trade in response to these shifting global trends. To meet the rising demand for EWPs, regions can: (1) increase production of inputs, (2) divert wood products that would have been consumed for more traditional uses (e.g. sawnwood in framing construction) to be used to produce EWPs, and (3) import more inputs.

First, under the medium demand scenario, the projected changes in sawnwood production reveal notable regional and compositional shifts compared with the BAU scenario. For coniferous sawnwood (Figure 4.9a), global production is projected to increase more steadily by as much as 25 million m^3 annually under the medium demand scenario, compared with the current level of 360 million m^3, with Asia, Europe and North America contributing significantly to this growth. Similarly, for non-coniferous sawnwood (Figure 4.9b), production under the medium demand scenario sees a more pronounced rise by up to 90 million m^3, compared with the current level of 165 million m^3, particularly in Asia and Africa – regions expected to meet growing demand from urbanization and construction. In both cases, the medium demand scenario reflects a diversification of production sources, with a shift towards regions outside traditional production powerhouses like North America. The adoption of EWPs amplifies demand, incentivizing higher production in emerging markets.

Figure 4.9 Change in sawnwood production, by region, medium demand versus business-as-usual scenarios, 2030–2070

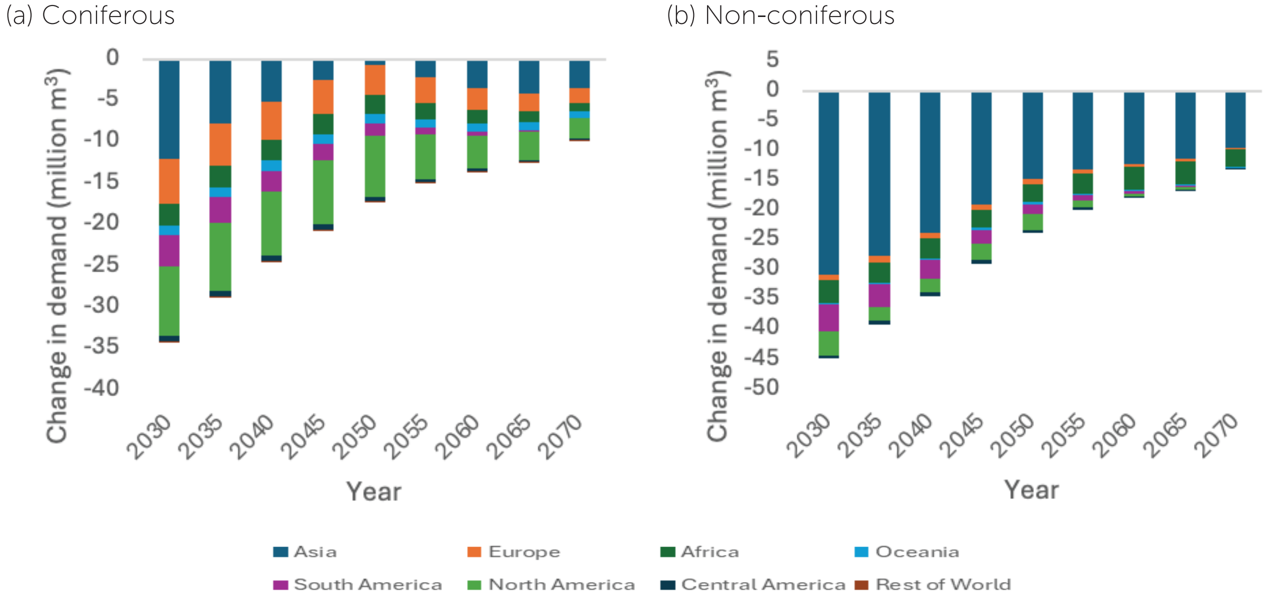


Source: Authors' own elaboration.

The shift towards increased adoption of EWPs is projected to also rely on a reallocation of sawnwood traditionally used in conventional construction practices, such as framing in residential buildings, to serve as inputs in production. Referred to as displaced demand, since EWPs are assumed to use sawnwood as an input in manufacturing, increasing the demand for EWPs will indirectly draw additional sawnwood to be used as an input, leaving less sawnwood to be used for conventional end uses (e.g. lumber for framing). Figure 4.10 highlights how sawnwood demand for traditional uses declines significantly across regions under the medium demand scenario compared with the BAU scenario, with this trend being especially pronounced for non-coniferous sawnwood (Figure 4.10b). Regions like Asia and North America, which have historically relied heavily on sawnwood for traditional construction, show notable reductions in demand for these uses. Instead, this sawnwood may be repurposed as raw material for EWPs, enabling the industry to partially meet rising demand for advanced wood-based building materials. In FOROM, this reallocation helps alleviate the supply pressure that would otherwise arise solely from producing additional sawnwood, allowing the growing production of EWPs to be met without overburdening primary production systems. Note, the trend is diminishing over time as the additional demand for EWPs erodes as urbanization rates decline. In other words, every year, additional EWP demand is occurring, but at a slower pace over time, displacing less demand.

Shifting trade patterns play a crucial role in meeting the increased demand for wood products, as demonstrated in Figures 4.11 and 4.12. Figure 4.11 highlights changes in net trade of sawnwood by region under the medium demand scenario relative to the BAU scenario. Regions like Asia, which are expected to experience growing domestic demand, show a trend towards net imports of sawnwood. For instance, coniferous sawnwood imports in Asia remain robust over time. In contrast, Europe, a major producer and exporter of sawnwood, continues to play a significant role in global supply, maintaining positive net trade balances for both coniferous and non-coniferous sawnwood. South America also sees moderate increases in net exports of non-coniferous sawnwood, helping to offset supply shortages in regions with greater demand.

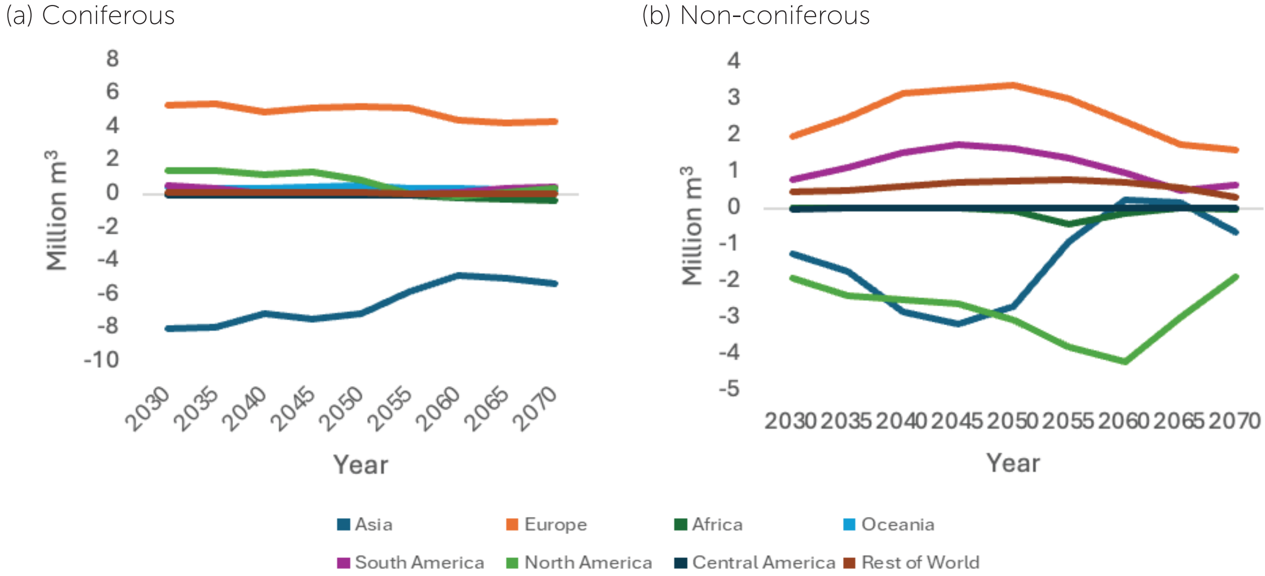
Figure 4.10 Change in sawnwood demand for traditional uses, by region, medium demand versus business-as-usual scenarios, 2030–2070



Note: The trend is diminishing over time as the additional demand for engineered wood products (EWPs) erodes as urbanization rates decline. In other words, every year, additional EWP demand is occurring, but at a slower pace over time, displacing less demand.
Source: Authors' own elaboration.

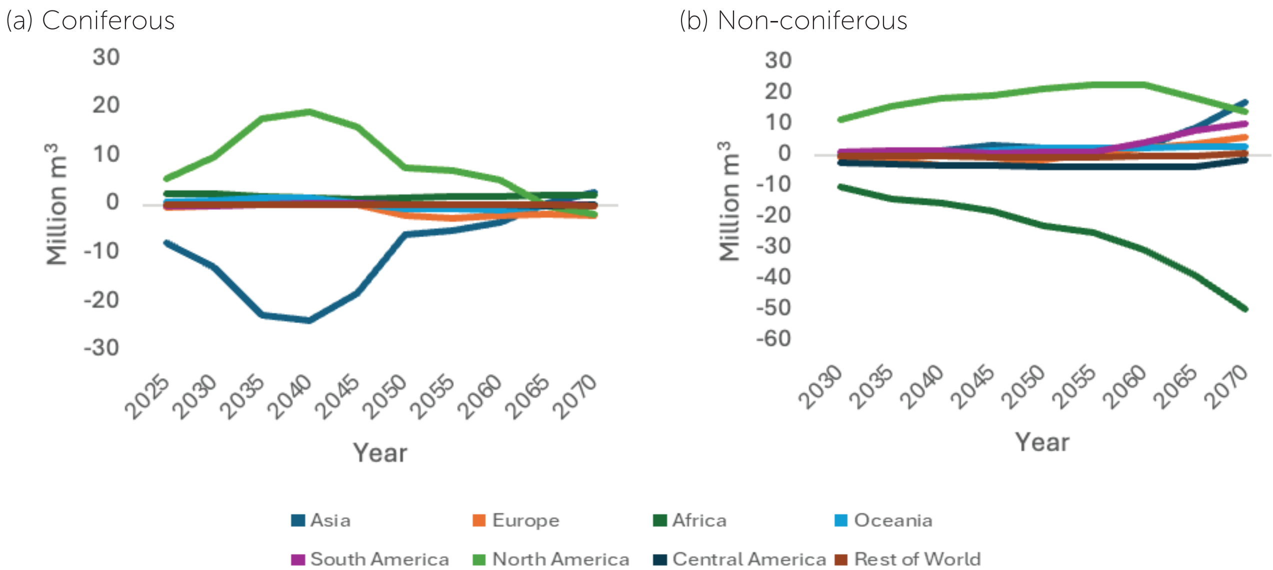
Figure 4.12 further underscores the critical role of trade in balancing supply and demand, focusing on industrial roundwood. Asia emerges as a dominant net importer of industrial roundwood, particularly for coniferous types, as its domestic production struggles to keep pace with demand. Conversely, North America is a key exporter of both coniferous and non-coniferous industrial roundwood, reflecting its growing role in global markets. Such evolving trade dynamics emphasize the interconnected nature of global markets and the importance of addressing potential imbalances through policies that enhance trade efficiency and sustainable resource management.

Figure 4.11 Change in net trade of sawnwood, by region, medium demand versus business-as-usual scenarios, 2030–2070



Note: Net trade is calculated as production minus use ("consumption"). Negative values indicate more imports and positive values indicate more exports.
Source: Authors' own elaboration.

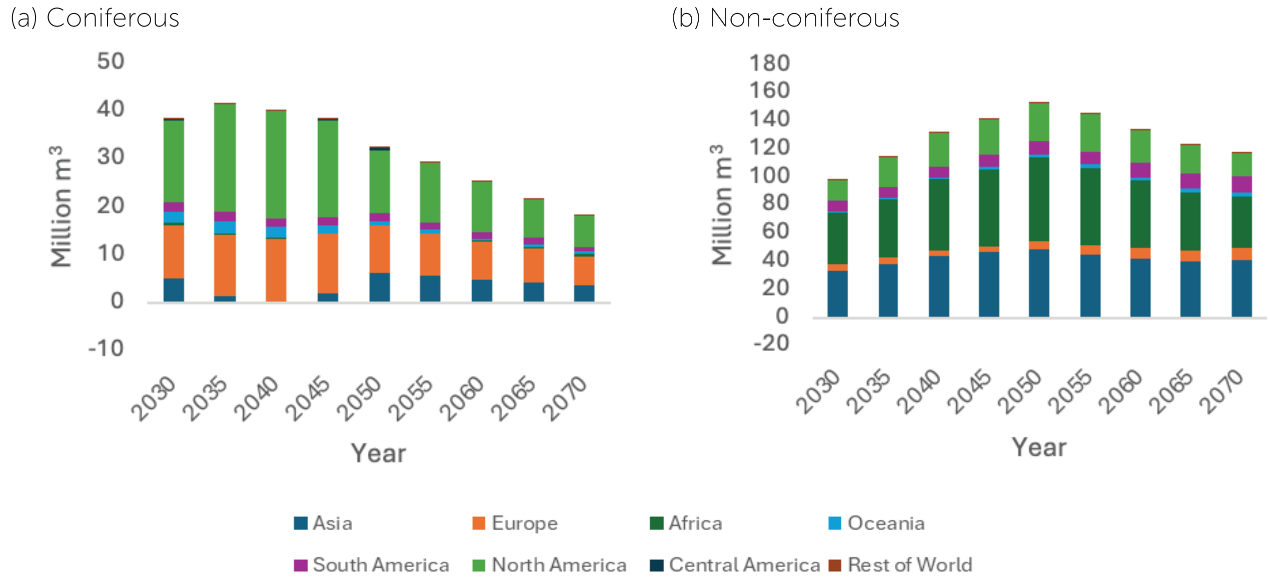
Figure 4.12 Change in net trade of industrial roundwood, by region, medium demand versus business-as-usual scenarios, 2030–2070



Note: Net trade is calculated as production minus use. Negative values indicate more imports and positive values indicate more exports.
Source: Authors' own elaboration.

There are notable increases in harvest levels for both coniferous and non-coniferous species under the medium demand scenario relative to the BAU scenario (Figure 4.13). For coniferous species (Figure 4.13a), regions such as North America and Europe play a critical role in this growth, leveraging well-established forestry sectors to meet the higher demand. In contrast, non-coniferous harvests (Figure 4.13b) also show significant increases under the medium demand scenario relative to BAU, with much of this growth concentrated in developing economies in Africa and Asia.

Figure 4.13 Change in harvest, by region, medium demand versus business-as-usual scenarios, 2030–2070



Source: Authors' own elaboration.

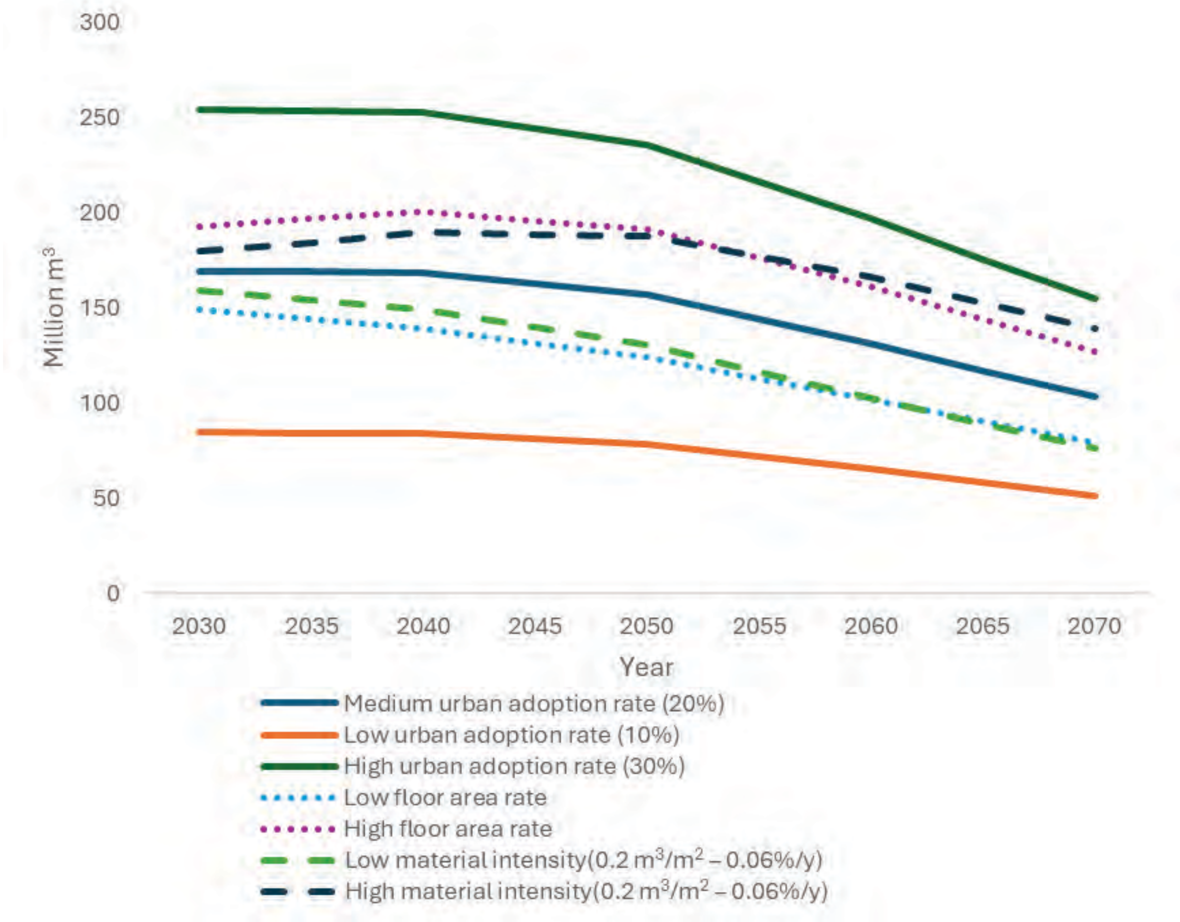
4.3 Projection sensitivity to key parameters

This section describes how different scenarios for floor area expansion and wood use intensity rates influence the demand for wood-based construction materials.

In scenarios with higher urban adoption rates, particularly in Asia and Africa, the demand for sawnwood and industrial roundwood increases significantly (Figure 4.14). The model estimates that Asia, despite its rapid urbanization and high demand, will continue to depend heavily on imports to meet building construction needs, highlighting a widening global trade imbalance in wood products. Overall, the change in wood product demand shows an increase across all scenarios, but declining after mid-century due to declining global population levels as assumed under shared socioeconomic pathway (SSP) 2.

Moreover, the wood use intensity scenarios, which explore varying rates of wood usage per square metre of floor area, indicate that shifts towards more wood-intensive construction practices could lead to substantially higher demand for wood products (Figures 4.14 and 4.15). The high material intensity scenario shows a marked increase in global wood demand, particularly for regions with established timber industries like Brazil and Canada, while regions with less efficient production systems may struggle to meet demand.

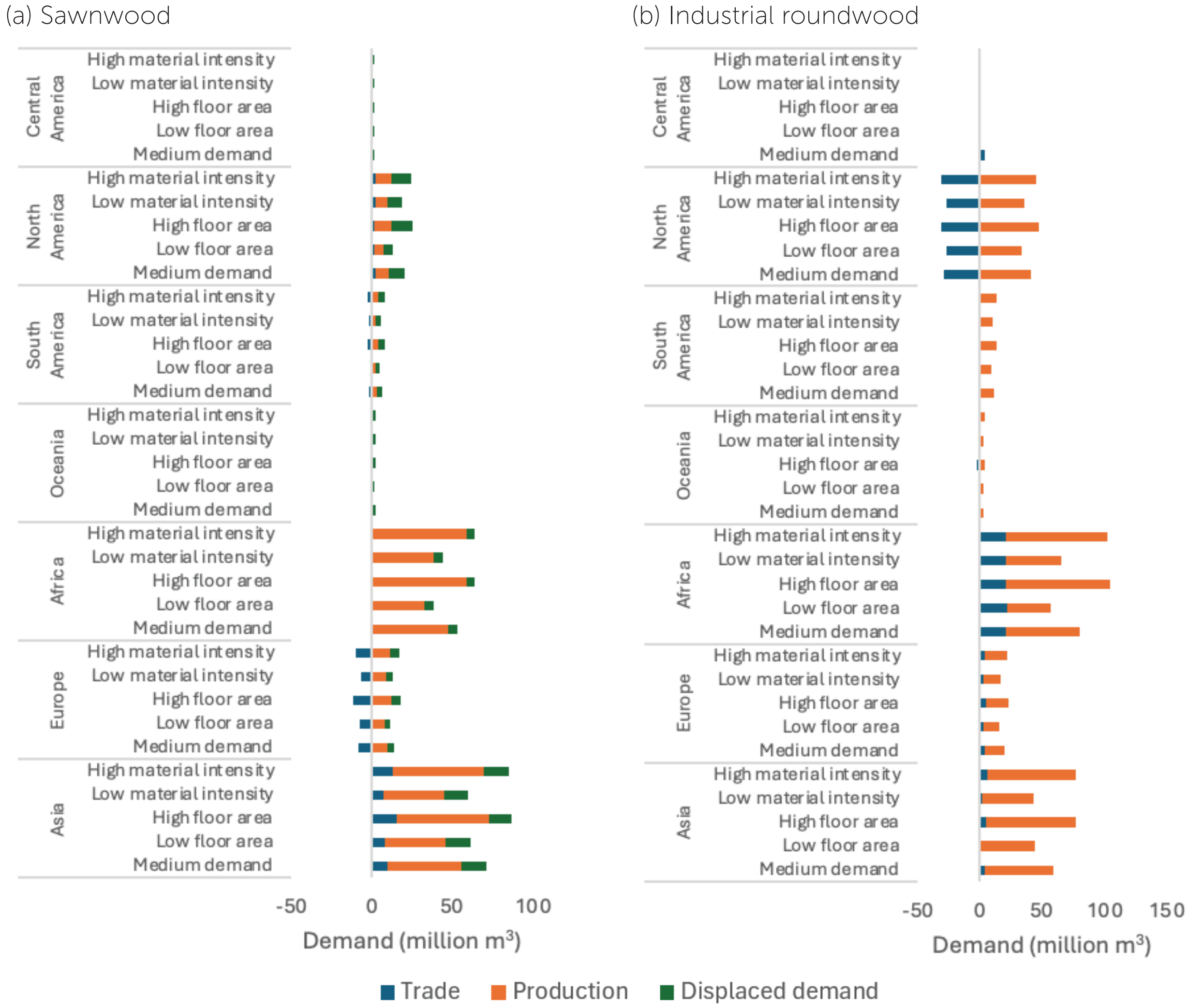
Figure 4.14 Increased wood product demand for building construction across scenarios, compared with the business-as-usual scenario, 2030–2070



Note: These values were used in Chapter 5 to calculate the potential emission reductions, specifically the additional annual emission reductions (Figure 5.1, inset plots).

Source: Authors' own elaboration.

Figure 4.15 How increased demand for sawnwood and industrial roundwood is met by region across alternative floor area and material intensity scenarios, 2050, medium urban adoption scenario versus business-as-usual



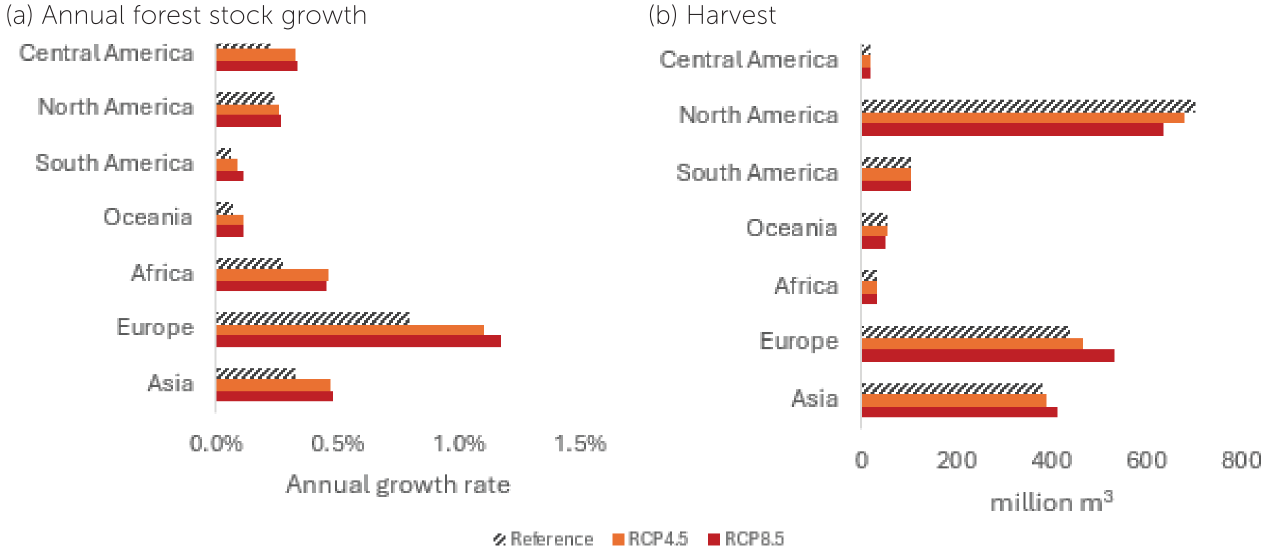
Notes: Displaced demand is the amount of sawnwood used as an input in manufacturing engineered wood products that otherwise was projected to be consumed as a final product (e.g. lumber) in the business-as-usual scenario. Trade is calculated as the difference between imports and exports to reflect how trade can be used to meet increased demand for manufacturing engineered wood products. Negative values for trade suggest imports minus exports are lower than under the business-as-usual scenario. This could occur by decreasing imports and/or increasing exports.

Source: Authors' own elaboration.

4.4 Climate change impacts on wood supply

This section illustrates how climate-induced changes in forest productivity affect regional forest resource dynamics under three scenarios: (1) reference (no additional climate change), (2) Representative Concentration Pathway (RCP) 4.5 (moderate climate change), and (3) RCP8.5 (severe climate change). Note that these climate scenarios only consider tree growth changes from CO_2 fertilization and temperature and not other climate-related impacts including drought, fires and disease that could have detrimental impacts on forest growth.

Figure 4.16 Forest stock growth rates and harvests, by region, under medium demand and climate scenarios, 2050



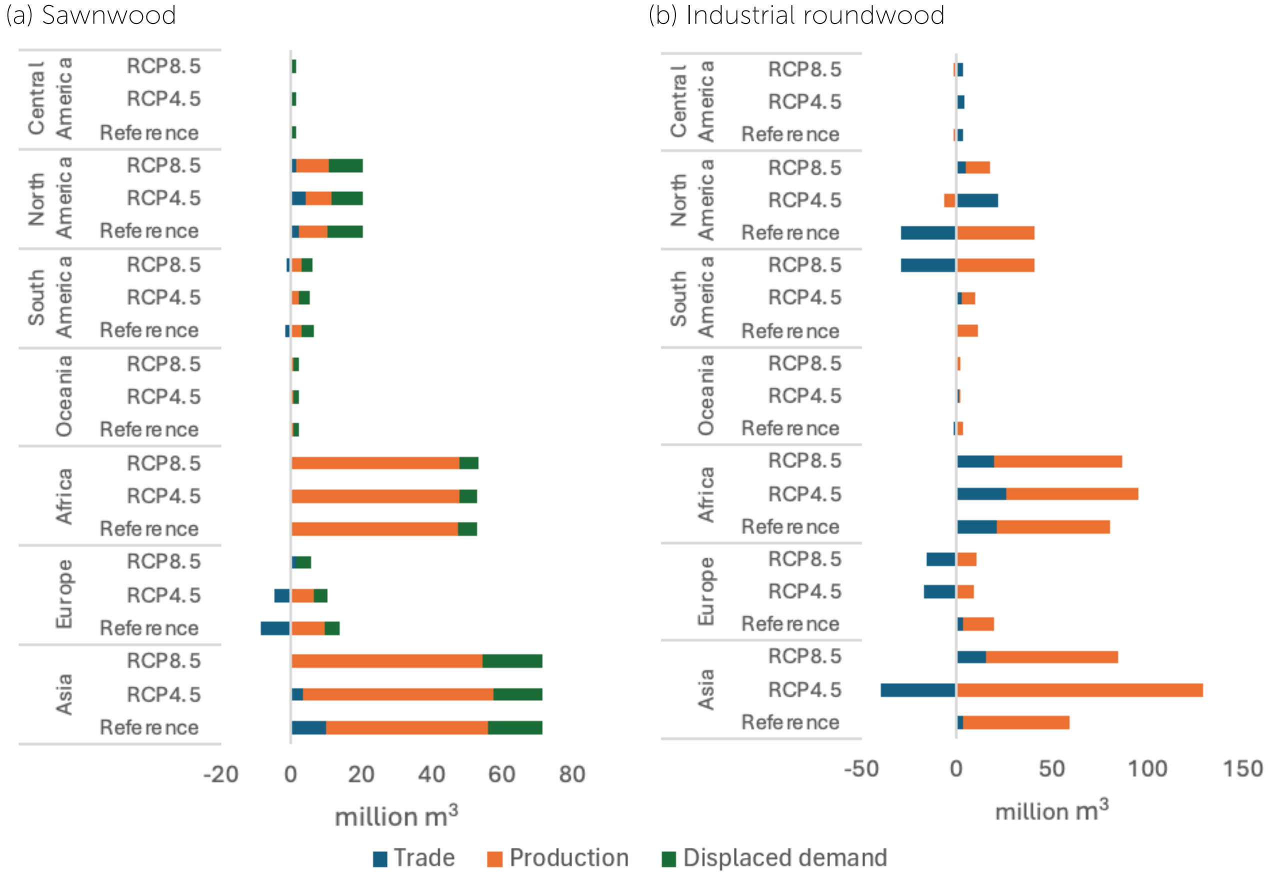
Source: Authors' own elaboration.

Forest stock growth rates vary substantially across regions under different climate scenarios. In Europe, forest growth rates rise from approximately 0.8 percent in the reference scenario to around 1.2 percent under RCP8.5, demonstrating the region's sensitivity to increased temperatures and CO_2 fertilization effects (Figure 4.16a). Similarly, Asia and Africa experience material increases under the RCP scenarios. In contrast, regions like North America, South America and Oceania show smaller changes, with growth rates increasing only marginally relative to the reference scenario.

Harvest levels[12] (Figure 4.16b) will likely follow a similar pattern, with Europe exhibiting the largest gains, increasing from 686 million m^3 under the reference scenario to 761 million m^3 under RCP8.5. Asia also sees a substantial rise, from 1751 million m^3 in the reference scenario to over 1800 million m^3 under RCP8.5. Conversely, North America sees a decline in harvest levels across climate scenarios as increases in Europe and Asia crowd out some North American production, while other regions see limited changes in harvests.

[12] The model does not assume that more growth always means more harvest; instead, higher growth can make harvesting cheaper in some regions, so harvest levels may rise if it is economically attractive.

Figure 4.17 How additional demand for sawnwood and industrial roundwood is met by region across climate scenarios, 2050, medium urban adoption scenario versus business-as-usual



Notes: Displaced demand is the amount of sawnwood used as an input in manufacturing engineered wood products that otherwise was projected to be used as a final product (e.g. lumber) in the business-as-usual scenario. Trade is calculated as the difference between imports and exports to reflect how trade can be used to meet increased demand for manufacturing engineered wood products. Negative values for trade suggest imports minus exports are lower than under the business-as-usual scenario. This could occur by decreasing imports and/or increasing exports.

Source: Authors' own elaboration.

The projected reversal in trade flows reflects the combined influence of demand growth, climate-driven shifts in forest productivity, and regional substitution dynamics. Under the RCP8.5 scenario, North American forests experience significant productivity losses, which forces the region into a net import position. In contrast, European forests are expected to retain or even improve relative competitiveness under warming, while domestic demand growth is comparatively modest in our scenarios. This creates scope for higher net exports by displacing imports that would otherwise be required in other regions. The study emphasizes, however, that this effect is scenario specific: in less severe climate pathways, Europe does not emerge as a major exporter, and in some runs trade balances only shift after 2050.

The projected climate change impacts do not affect the magnitude of a region's additional demand for sawnwood (Figure 4.17a) as this is a fixed assumption constructed by the scenarios. It does, however, affect how that demand is met by potentially changing production, trade or displaced demand of traditional uses of sawnwood. It also affects which regions produce the underlying upstream industrial roundwood used to produce sawnwood.

Specifically, sawnwood production in Europe increases by about 4 million m^3 under RCP8.5, while maintaining modest levels of displaced demand (Figure 4.17a). For industrial roundwood, Europe exhibits significant production gains (over 60 million m^3 under RCP8.5) alongside increases in net exports, leveraging its improved productivity (Figure 4.17b). The RCP4.5 scenario results in smaller increases, with production rising by only about 30 million m^3 for industrial roundwood relative to the reference scenario.

Asia also experiences a significant increase in production of industrial roundwood under RCP8.5, increasing by nearly 40 million m^3 under RCP8.5 relative to the reference scenario. Some of this material is exported or used to produce additional sawnwood to meet the rising demand for EWPs.

Due to increased production in other regions, production of industrial roundwood in North America declines by more than 60 million m^3 under RCP8.5 relative to the reference scenario. This changes North America's strategy in meeting the increased demand for EWPs. Under the reference scenario, North America continues to be a robust producer of industrial roundwood, meeting domestic demand and supplying exports to the rest of the world. This pattern shifts under RCP8.5. In order to meet the rising demand from EWPs, domestic production rises by less than under the reference scenario, forcing North America to become reliant on imports from other regions to meet domestic demand.

4.5 Discussion

In light of the potential for greater use of wood products and adoption of EWPs in construction, results suggest that meeting the rising demand for wood products may require significant adjustments in global forestry and change the global pattern and volume of international trade in wood products. North America and South America, with their vast forest resources, are poised to play critical roles in supplying the growing demand for sawnwood and industrial roundwood, but even these regions may face challenges in scaling up production quickly enough to meet the sharp increase in demand. For example, availability of skilled labor and advanced machinery may play a limiting role. Sustainable forestry practices, investments in forest management, governance, land tenure and advances in wood-processing technologies will be essential to ensure that supply can meet demand without compromising environmental sustainability. Furthermore, the growing reliance on wood in construction will likely require increased international collaboration, with regions like Europe and North America playing a key role in addressing production shortfalls in emerging markets like Africa and Asia.

Projections of EWP demand are broadly consistent with other modelling exercises, yet they also reveal distinct global vulnerabilities and scale mismatches between production capacity and future demand. For example, Philippidis *et al.* (2024), using an integrated bioeconomy model for the European Union (EU-27), project that ambitious policy scenarios – such as high-intensity harvesting and biomass expansion – could raise EU-27 forest industry output to roughly 687 to 717 million m^3 per year by 2050. Despite this increase, domestic production remains insufficient to meet demand, reducing the European Union (EU-27)'s trade surplus. In contrast, the medium urban adoption scenario developed in this study points to a global increase of approximately 0.3 billion m^3 in sawnwood and 1.1 billion m^3 in industrial roundwood by 2050 – an expansion that far exceeds the EU-specific magnitudes in Philippidis *et al.* Similarly, Nepal *et al.* (2021) estimate that widespread mass timber adoption could raise global roundwood harvests by 4 to 15 percent, a range comparable to the upward pressures observed under high-intensity policy scenarios. Meanwhile, UNECE and FAO (2021b) provide a descriptive benchmark of the current scale of EWP production: glue-laminated timber (glulam) output in Austria reached 1.59 million m^3 in 2020, Germany produced 1.32 million m^3, and global cross-laminated timber (CLT) production capacity was about 2.8 million m^3 in 2020 – expected to reach 4 million m^3 by 2025. These figures are small relative to the demand surges projected by this study, underscoring the magnitude of the required industrial transformation. By explicitly integrating the effects of displaced conventional sawnwood use and climate-induced productivity shifts, the present analysis extends earlier work, highlighting both potential moderating mechanisms and the heightened risks of trade imbalances and supply bottlenecks that could accompany large-scale EWP adoption.

The results of the study imply that the global forest products sector may be at a critical juncture. The shift towards greater use of wood-based materials in construction presents both opportunities and challenges for global markets. By anticipating these changing demand trends and preparing for potential supply imbalances, policymakers, industry stakeholders, as well as forest managers and users can help ensure that the demand for sustainable wood products is met while also maintaining the long-term health of forest ecosystems. With the right investments in reforestation, forest management, technology, policy and trade infrastructure, it is possible to support a sustainable, efficient and resilient global wood product market that meets the evolving needs of a rapidly urbanizing world.

While the results provide valuable insights, several limitations and uncertainties must be acknowledged. First, the approach adopted in this analysis focuses on how sawnwood alone can be used to meet the demand for structural EWPs. The choice to focus on sawnwood was due to reasons including the high relevance in terms of absolute demand volumes as well as the model's ability to reflect these more traditional products. Indeed, other products can be used specifically for non-structural EWPs including wood-based panels. This consideration remains outside the scope of the current analysis. Second, the fact that the FOROM model is calibrated on historical data can lead to uncertainties when baselines are very low. With the marginal cost of producing sawnwood in Africa being very high, the projected production increases would not only depend on a strong future demand but also on an increased future harvesting, milling and manufacturing capacity, with corresponding high capital investments. Third, the share of coniferous and non-coniferous species as input for EWP production is modeled based on region-specific recent historical production to account for domestic production capabilities, while not considering the sectors' current preference for coniferous species. Fourth, uncertainty in reported harvest volumes – particularly due to unaccounted or illegal logging activities noted in Figure 2.1 – adds further ambiguity to global wood flow estimates and may affect the accuracy of modelled supply balances (Yayla *et al.*, 2025).

In addition, the model's projections are contingent on assumptions regarding timber demand, land-use change, climate impacts and policy interventions, each of which carries inherent uncertainty. Structural limitations stem from the interactions between forest growth, management practices and disturbances over time, while socioeconomic factors such as GDP growth, population dynamics and technological advancements introduce additional variability in forecasted harvest levels. Moreover, the model's sensitivity to key parameters – including price elasticities,[13] harvest costs, regeneration rates and climate change impacts – can lead to divergent long-term outcomes. Uncertainties related to climate change effects on forest productivity, as well as potential inaccuracies in inventory estimates and disturbance projections, may further affect the results. Given these challenges, this study relied on scenario analysis and sensitivity testing for assessing the robustness of the projections and understanding the range of possible future trajectories for forest resources.

The analysis provides an attempt to better understand the long-term implications on the global forest sector of increased wood use in building construction. The analysis could benefit from further exploration of other emerging sectors within the bioeconomy, such as bioenergy, which is also experiencing a transition due to growing environmental concerns and the demand for renewable energy sources. Other trends in the bioeconomy, like the use of forest biomass for energy and other bioproducts, could also substantially influence the future demand for forest-based materials, and addressing these evolving trends will be critical for a comprehensive understanding of how global wood product markets will develop in the coming decades. In turn, better understanding changing demand patterns will directly inform the structure and type of future forests needed as well as their species mix and age class (e.g. short rotation for pulp and paper compared with thinning regimes needed for strength grade timber going into CLT). Furthermore, a more elaborate investigation into the potential effects of climate change on the capacity of forests to meet future demand is needed. Specifically, an analysis that captures the full spectrum of potential challenges and opportunities that climate change may pose to the global forest sector including changes in precipitation and water supply, human population patterns and natural disturbances.

[13] Price effects are not explicitly analysed here. While included in the FOrest Resource Outlook Model (FOROM), high uncertainty and limited data on EWPs prevent robust conclusions about future price movements.

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5 Climate change mitigation potential of using engineered wood products in construction: A preliminary analysis

This chapter presents the global and country-level results of the preliminary analysis of emission reductions for all FOrest Resource Outlook Model (FOROM) scenarios of urban adoption rate, floor area per capita and wood use intensity. Additional country-level figures are reported in the Appendix (Section 9.3). Results refer to the FOROM modelling regions (Table A2 and Table A3).

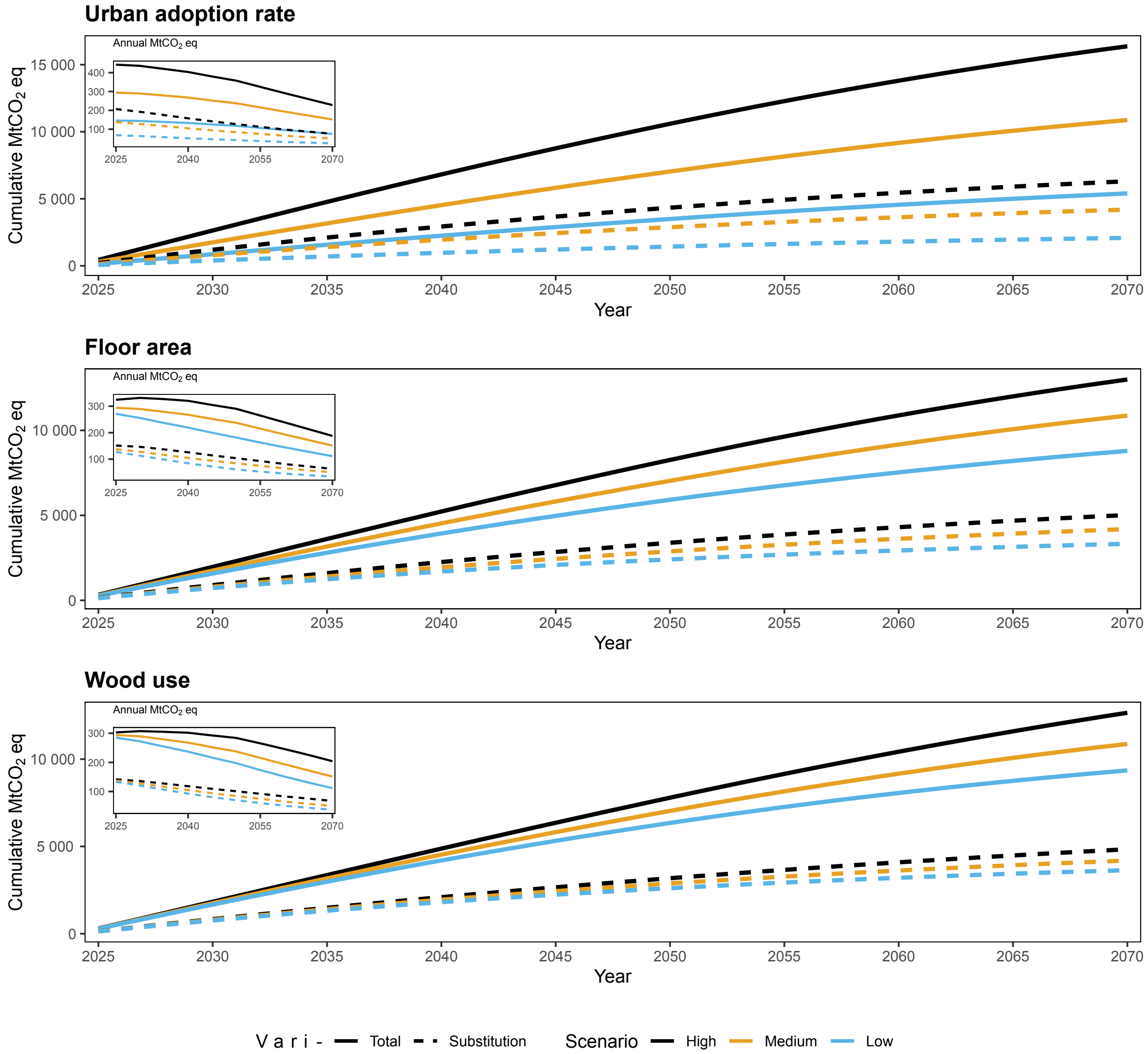
5.1 Global-level results

At the global level, the medium demand scenario could achieve annual emission reductions of 236 $MtCO_2$-eq per year for the period 2025 to 2070. Cumulative emission reductions could amount to 10.9 $GtCO_2$-eq for the same period. These values are equivalent to 0.3 percent of the annual and cumulative projected global emissions for the same period under the shared socioeconomic pathway (SSP) 2 baseline scenario of global emissions.

In a scenario where current policies and action are implemented (i.e. the Nationally Determined Cointributions individual countries issued in response to the Paris Agreement), the annual and cumulative emission reductions could account for 0.4 to 0.5 percent of projected global emissions. If long-term climate pledges and targets are met, the annual and cumulative emission reductions are equivalent to a slightly higher share of 0.6 to 0.8 percent of future emissions globally. For the building sector in particular, the annual emission reductions are equivalent to around 7 percent of the sector's global annual projected emissions (WEC, 2025).

The high adoption scenario could achieve the highest annual and cumulative emission reductions globally for the period 2025 to 2070 (i.e. 356 $MtCO_2$-eq per year and 16.4 $GtCO_2$-eq, respectively), which are 50 percent higher than those of the medium demand scenario. The high floor area and high wood use scenarios could each achieve annual emission reductions of around 280 $MtCO_2$-eq per year, or 13 $GtCO_2$-eq cumulatively for the period 2025 to 2070. These values are almost 20 percent higher than those of the medium demand scenario. Across all scenarios, carbon storage accounts for at least 61 percent of the cumulative emission reductions for the period 2025 to 2070, with substitution effects accounting for the rest (39 percent) (Figure 5.1).

Figure 5.1. Cumulative global emission reductions from additional engineered wood product demand for scenarios of urban adoption rate, floor area per capita, and wood use intensity



Notes: The emission reductions shown include a breakdown of contribution via substitution effects. The additional emission reductions per year compared with the business-as-usual scenario are shown in the inset plots, which are based on the values reported in Figure 4.14.
Source: Authors' own elaboration.

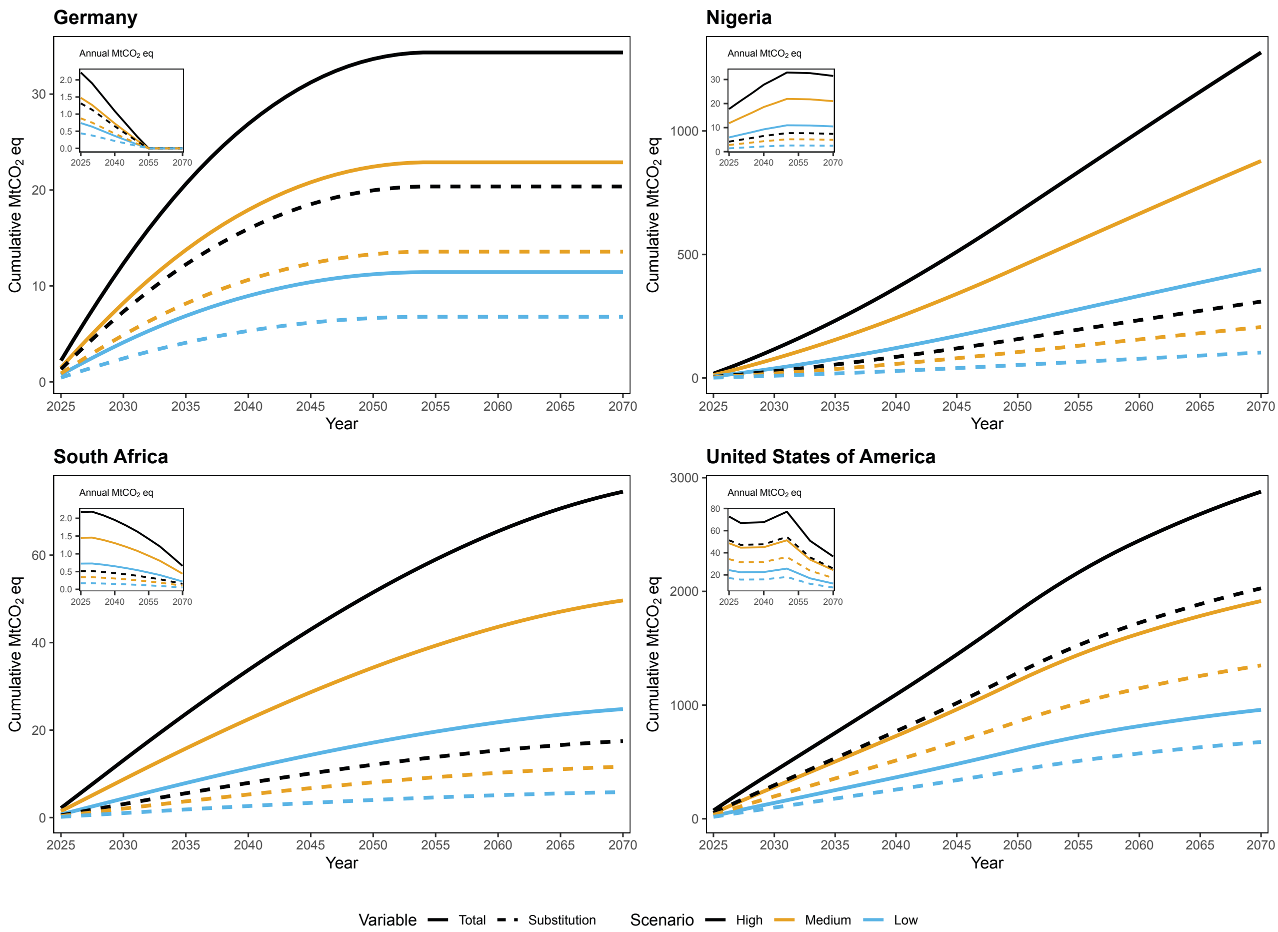
In terms of global carbon budgets, by 2070, total cumulative emission reductions for the high adoption scenario would be equivalent to around 7.5 and 1.5 percent of what is needed to limit global warming to 1.5 °C and 2 °C warming scenarios, respectively, compared to pre-industrial levels ("global carbon budget"). Total cumulative emission reductions for the high floor area scenario would be equivalent to around 5.9 and 1.2 percent of the remaining global carbon budget for the 1.5 °C and 2 °C warming scenarios, respectively. For the high wood use scenario, total cumulative emission reductions would amount to around 5.8 and

1.2 percent of the remaining global carbon budget for the 1.5 °C and 2 °C warming scenarios, respectively.

5.2 Country-level results

For the four case study countries, the trends in annual emission reductions of future engineered wood product (EWP) demand reflect the projected EWP demand of each country as estimated in Chapter 4 (Figure 5.2, Appendix Figures A1–A2). The shares of emission reductions covered by carbon storage and substitution effects vary across countries. For example, for Germany, carbon storage accounts for about 41 percent of the cumulative emission reductions under the medium demand scenario for the period 2025 to 2070. Substitution effects account for the rest (59 percent). For Nigeria and South Africa, carbon storage accounts for about 77 percent of the cumulative emission reductions for the same scenario and period. Substitution effects account for the rest (23 percent).

Figure 5.2 Country-level cumulative and annual emission reductions for four case study countries, resulting from additional engineered wood product demand for urban adoption rate scenarios



Notes: The emission reductions shown include a breakdown of contribution via substitution effects. The additional emission reductions per year are shown in the inset plots.
Source: Authors' own elaboration.

The following section outlines the climate mitigation potential of future EWP demand for each of the four case study countries in relation to their respective mitigation targets.

Germany

According to the *Federal Climate Action Act* amended in 2024, Germany aims to reduce greenhouse gas (GHG) emissions by at least 65 percent by 2030 and at least 88 percent by 2040 in comparison with 1990 levels (Federal Ministry of Justice, Germany, 2024). With emission levels in 1990 reported to be 1252 $MtCO_2$-eq excluding land use, land use change and forestry emissions (UBA, 2025), this translates to a targeted reduction of 814 $MtCO_2$-eq and 1102 $MtCO_2$-eq by 2030 and 2040, respectively.

Under all high scenarios of urban adoption rate, wood use intensity and floor area per capita, Germany's projected cumulative emission reductions could contribute to 1.1 to 1.5 percent of its 2030 target. For its 2040 target, Germany's projected cumulative emission reductions could contribute to a slightly higher share under the same scenarios (i.e. 1.7 to 2.4 percent of its 2040 target). The highest share for both the 2030 and 2040 targets would stem from the high urban adoption rate scenario.

Nigeria

Nigeria's first Nationally Determined Contribution (NDC), updated in 2021, sets an unconditional contribution target of 20 percent below business-as-usual (BAU) projected emissions by 2030. Its conditional contribution target (i.e. conditional on international support) raises the target to 47 percent below BAU projected emissions by 2030. Moreover, Nigeria's NDC projects business-as-usual GHG emissions in 2030 to be 452.7 $MtCO_2$-eq (Federal Government of Nigeria, 2021). Nigeria's targets therefore translate to a targeted reduction in emissions of around 91 $MtCO_2$-eq and 213 $MtCO_2$-eq by 2030 for the unconditional and conditional targets, respectively.

The projected cumulative emission reductions of future EWP demand in Nigeria could contribute to a substantial share of Nigeria's targets. Under all high scenarios of urban adoption rate, wood use intensity and floor area per capita, cumulative emission reductions of future EWP demand could contribute 38 to 55 percent of the conditional targets. For the unconditional target, the share is larger (89 to 92 percent). Moreover, under the scenario of high urban adoption rates, the projected cumulative emission reductions of future EWP demand could exceed the unconditional target by 29 percent.

South Africa

South Africa's NDC does not set an emission reduction target in relation to a reference point. Instead, the country has set a fixed range of GHG emissions by 2025 and 2030. In its first NDC, updated in 2021, South Africa set its annual GHG emissions by 2030 to be within the range of 350 to 420 $MtCO_2$-eq (Government of the Republic of South Africa, 2021).

To place South Africa's NDC targets in the context of emission reductions, country-level projections from the World Emissions Clock (WEC) were used as a reference point. The WEC projects South Africa's emissions from all sectors combined to be 574 $MtCO_2$-eq by 2030 (WEC, 2025). When compared with South Africa's NDC targets for 2030, this would equate to an emission reduction of 154 to 224 $MtCO_2$-eq that would be necessary for South Africa to achieve its targets.

The projected cumulative emission reductions of future EWP demand in South Africa could contribute to a small but sizable share of its mitigation targets. Across all high scenarios of urban adoption rate, wood use intensity and floor area per capita, cumulative emission reductions of future EWP demand could contribute to 5.9 to 8.5 percent of the necessary emission reductions that South Africa would require to meet the minimum threshold of its target.

United States of America

According to the United States' first NDC, updated in 2021, the country aimed to reduce net GHG emissions by 50 to 52 percent in 2030 and 61 to 66 percent in 2035 compared with 2005 levels (Government of the United States of America, 2021). With 2005 net emissions reported as 6587 MtCO_2-eq by the Inventory of US Greenhouse Gas Emissions and Sinks (Government of the United States of America, 2021), this translates to an emission reduction target in the range of 3294 to 3425 MtCO_2-eq by 2030 and 4018 to 4347 MtCO_2-eq by 2035.

The projected cumulative emission reductions of future EWP demand in the United States could contribute to a sizable share of its mitigation targets. Under all high scenarios of urban adoption rate, wood use intensity and floor area per capita, cumulative emission reductions of future EWP demand could contribute to 8.5 to 12.7 percent of its 2030 target. For the 2035 target, the contribution is estimated to be even higher at around 12.3 to 18.8 percent under the same scenarios.

5.3 Discussion

The preliminary analysis above highlights the potential benefits of increasing EWP demand in contributing towards climate change mitigation. In particular, the analysis demonstrates to what extent the carbon storage and substitution effects of increasing EWP demand could contribute towards emission reductions. At the global level, annual emission reductions could amount to 236 MtCO_2-eq per year, equivalent to the annual emissions from energy use in more than 31 million homes in the United States (EPA, 2025).

While the emission reductions from increasing EWP demand is small (<1 percent) in comparison with various global emission projection pathways, the results demonstrate that EWPs can be a component of broader mitigation strategies, particularly considering that the estimated EWP adoption rates are rather conservative. The global-level results imply the need for more stringent action to cut emissions across all industries beyond the building sector and material replacement alone.

Within the building sector, the replacement of fossil-based materials with wood products would need to occur in parallel with emission reduction strategies in other industrial stages, in order to maximize the industry's overall climate change mitigation potential. Strategies could include adopting low-carbon manufacturing and improving energy efficiency across industrial stages. Such efforts could help increase the small share (7 percent) of global emission reductions of increasing EWP demand relative to the building sector's total global emissions. The same could also be said at the country level. For example, South Africa's building and construction sector could see further emission reductions of up to 90 percent if the sector were to implement low-carbon materials alongside efficiency improvements and switching to renewable power on both building operations and construction (NBI, n.d.).

Furthermore, at the country level, the contribution of increasing EWP demand towards national climate change mitigation targets varies across countries. In the cases of Germany and South Africa, the contributions of emission reductions from all EWP demand scenarios towards their respective targets are small (<3 and <6 percent, respectively). But in the cases of Nigeria and the United States, the contribution could be substantial. For Nigeria in particular, a high urban adoption scenario could help the country exceed its unconditional NDC target by 29 percent. These findings suggest the important role of increasing EWP demand to enable some countries to reach and even surpass their climate targets.

At the global level, carbon storage accounts for a larger portion of the reductions than substitution effects, with the shares varying by country. It should be noted that the values reported in this analysis represent an average of reported substitution factors in the literature – and hence a generalization of products and energy mixes being replaced – at the global and country levels. If the analysis relied on the substitution factor of one extreme case, for example, wood products replacing concrete that is produced with emission-intensive energy sources like coal, the resulting share of substitution effects could be much larger. Furthermore, owing to the lack of country-specific studies and data, the substitution factors used for Nigeria and South Africa were global averages, which are largely based on studies conducted in North America and northern Europe (Leskinen *et al.*, 2018). This may not accurately reflect each country's actual availability of construction materials and energy mix that could be replaced by wood products. For example, substitution factors could be much larger for South Africa as 70 percent of its energy mix is coal (IEA, 2025).[14] This highlights the need for further research on life cycle assessment (LCA) and substitution effects that are more geographically diverse so as to better represent specific countries. Supporting academic research in LCA and carbon quantification in regions with comparatively limited studies could help provide a more comprehensive, geographically representative overview of the climate benefits of increasing wood use, and the forest bioeconomy more broadly.

Furthermore, many studies on substitution effects are focused on a limited number of life cycle stages, namely the production, use, and, to some extent, end-of-life phases. Further analysis is warranted on the carbon flow dynamics in forest growth and harvests, which would require an understanding of the impacts of climate-related disturbances on forest supply, and how forest management practices may evolve over time in harvesting regions. It would also necessitate a more detailed analysis on forest product supply chain linkages and trade flows to identify the origins of forest harvests, given the global interconnected nature of forest products and the growing need to address the displaced impacts of forest product use (Jonsson *et al.*, 2021; Zhang *et al.*, 2020). At the same time, prospective studies need to consider to what degree carbon storage and substitution effects in wood products could compensate for potential net losses in carbon in forest ecosystems (Fehrenbach *et al.*, 2022), thereby addressing concerns over whether to leave forests intact or increase harvests and carbon storage in wood products as effective climate change mitigation strategies.

Given the time coverage of the analysis, which spans several decades, the analysis could benefit from further research on the temporal dynamics of carbon intensities of both wood products and their counterparts, such as the potential decarbonization of products driven by increasing material efficiencies. A better understanding of the end-of-life management of wood products in the building sector could also provide a more nuanced picture of carbon dynamics over time. This would require an understanding of building lifetimes, renovation practices, demolition rates and waste management systems, all of which vary across regions and over time. For example, the reuse and repurposing of construction materials could lock in carbon for extended periods of time, while energy incineration releases carbon back into the atmosphere within a shorter time frame. Landfilling could also have implications on carbon storage, via carbon that is stored in landfills, and emissions associated with anaerobic decomposition of wood waste (Ménard *et al.*, 2025).

[14] A higher substitution factor for South Africa is possible under the assumption that sawmills producing EWP derive energy from wood-processing residues, whereas the alternative construction material relies on the current energy mix that is predominantly coal.

6 Conclusions and outlook

The transition to a forest-based bioeconomy, such as the shift towards more wood-based buildings, is projected to reshape global forest markets. A conservative increase in urban adoption of engineered wood products (EWPs) could increase future demand for EWPs by 50 to 250 million m^3 in any given year by 2070, pushing sawnwood and industrial roundwood consumption beyond business-as-usual (BAU) projections globally. The projected changes in sawnwood and industrial roundwood consumption vary between regions[15] depending on future growth in population, gross domestic product (GDP) and urbanization. In some regions (e.g. Africa, Asia), a medium urban adoption scenario could result in a net sawnwood deficit.

In terms of climate impacts, global warming and increased CO_2 concentrations could increase forest productivity in some regions and hence their capacity to supply raw materials (e.g. parts of Europe and Asia). These climate impacts, however, do not take into account the effects of interacting disturbances.

A greater emphasis on wood product use in the built environment could support climate change mitigation efforts by reducing the sector's carbon emissions through carbon storage and substitution of more carbon-intensive materials. A medium demand for EWPs could achieve global annual emission reductions of 236 $MtCO_2$-eq per year (or 10.9 $GtCO_2$-eq cumulatively) for the period 2025 to 2070. At the country level, increasing EWP demand could help countries achieve their respective national mitigation targets to varying degrees. In some cases, such as in Nigeria, a high urban adoption scenario could help the country exceed its targets.

The analyses from this report highlight a number of opportunities that policymakers and practitioners could consider in promoting the transition towards a forest-based bioeconomy. These opportunities could help address the projected supply–demand imbalances for wood products, while also leveraging their climate change mitigation potential.

Enhancing material efficiency and circularity

Adopting principles of material efficiency and circularity could ensure that demand for wood products can be met with minimal need for additional harvesting (Yayla *et al.*, 2025). This could help close supply–demand gaps and address the potential supply–demand deficits of increasing wood product use in the built environment projected in some regions.

At the same time, enhancing material efficiency and circularity could enhance climate change mitigation during material production, along with other benefits such as reducing energy demand in production and operational energy use (Allwood *et al.*, 2013; Hertwich *et al.*, 2019; Pramreiter *et al.*, 2023a). This could enhance the overall climate change mitigation potential of increasing wood product use in the built environment, adding up to the projected emission reduction benefits of carbon storage and substitution effects.

[15] Referring to FOROM modelling regions (Table A2 and Table A3).

Integrating the 11R framework into the forest-based bioeconomy could help enhance material efficiency and circularity (Kochanski *et al.*, 2024).[16] For the built environment, the framework includes eleven principles ranging from "Refuse" (i.e. removing functions from buildings, materials or components that are redundant) to "Recycle" (i.e. producing building materials from construction and demolition waste), with the last-resort option of "Recover" (i.e. incinerate building materials for energy recovery) (Kochanski *et al.*, 2024).

Another option to increase wood product supplies without the need to expand harvest volumes is to divert short-life applications towards long-life uses, including construction. In other words, efforts could look into developing and incentivizing supply chains and markets that focus on higher-value, long-life wood products. Such efforts should also include developing and incentivizing end-of-life management strategies that enhance the recovery of post-consumer wood products while minimizing wood waste. All in all, these efforts could have the benefits of not only freeing up existing supplies but also locking in carbon for longer periods of time and hence contributing towards climate change mitigation (IPCC, 2022).

The climate benefits of such diversions are especially evident if forest harvests are redirected from woodfuel (Yayla *et al.*, 2025), the burning of which results in an almost immediate release of carbon into the atmosphere. One estimate suggests that 353 million m^3 of wood could be made available for industrial purposes if demand for woodfuel was reduced by 50 percent, for example through increased efficiency and the use of other renewable energy sources (Hetemäki *et al.*, 2021). Efforts to redirect woodfuel use should, however, be done in tandem with efforts to promote the cascading use of forest resources and strengthen energy and livelihood security, as many regions, including those in Africa, are still heavily dependent on woodfuel for basic energy needs and income (Fertahi *et al.*, 2023; Hetemäki *et al.*, 2021).

In cases where forest harvests could be raised to meet growing demand, it is essential to promote sustainable and resource-efficient forest management practices across all forest-producing regions. This could include, for example, encouraging the adoption of agroforestry systems in which trees grow together with crops and/or animals, which could also contribute to sustaining rural livelihoods, improving crop yields and offsetting pressure on natural forests (Mengitsu, 2023; Ndayambaje and Mohren, 2011).

Facilitating global trade of sustainable forest products

The potential supply–demand imbalances resulting from increasing EWP demand underscore the importance of international trade and global forest resource allocation. Regional capacities to supply wood to meet demand vary between regions due to variation in the extent and types of forest and their availability to supply wood products, as well as the level of development of timber markets in each region. In situations where increasing sustainable regional production capacities is challenging or may only bear results in the longer term, efforts are needed to keep global trade networks open and accessible between regions to meet projected demand in wood products.

Policymakers could consider trade policies and international cooperation frameworks that enable efficient flows of wood products from surplus regions to deficit regions. This could also entail reducing trade barriers and investing in infrastructure to improve logistics and connectivity within global supply chains.

Moreover, promoting the trade of wood products could be aligned with sustainability standards to ensure forest conservation and restoration. This could include, for example, permitting the trade of products only from certified sustainably managed forests, as well as harmonizing sustainability standards.

[16] The 11R framework is a set of eleven principles related to the circular economy that are relevant for the built environment: Refuse, Rethink, Reduce, Replace, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover (Kochanski *et al.*, 2024).

Outlook

Policymakers and practitioners in the bioeconomy and built environment will need to address the anticipated changes in wood product markets and their implications for climate change mitigation. This could include integrating wood products into bioeconomy, climate, and other sectoral strategies, as well as embedding wood-based solutions in construction, energy and industrial value chains. At the same time, efforts to meet the anticipated growing demand for wood products will need to be in line with policies aimed at conserving and protecting naturally regenerating forests for biodiversity, ecosystem services and climate change mitigation.

While advances have been made to improve and refine models on current and future wood use, the quality of such estimations ultimately depends on the data used to calibrate such models. Efforts are thus also needed to support countries in improving data collection, monitoring and reporting, and to reduce data inconsistencies.

Looking ahead, the transition to a forest-based bioeconomy will demand coordinated action. EWPs in construction can significantly support climate change mitigation, but only if demand is managed responsibly through sustainable supply, efficient use, international trade and fair distribution. Success will depend on early, integrated policies that address regional imbalances, climate risks and governance. Choices made now will determine whether EWPs advance a sustainable bioeconomy or intensify pressures on forests.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7 Glossary

The definitions provided here are for the convenience of readers and are not necessarily official FAO definitions.

Bioeconomy

The production, use, conservation and regeneration of biological resources, including related knowledge, science, technology and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy (FAO, 2024).

Cross-laminated timber (CLT)

A prefabricated engineered wood product consisting of at least three layers of solid-sawn lumber or structural composite lumber where the adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element. Panels are prefabricated based on the project design (FAO, 2024).

Engineered wood products (EWPs)

Products that are based on wood pieces or wood fibres that have been transformed from the original log, mixed or coated with adhesives, and then recombined to produce the desired product. They differ from paper and pulp products as the final form of engineered wood products are boards or sheets (Grebner *et al.*, 2021). This report focuses on structural EWPs (including cross-laminated timber and glulam), which are often referred to as mass timber (see Section 1.3).

Floor area (FOROM modelling scenario)

The change in floor space per capita over time, based on the scenarios used in Fishman *et al.* (2021). The "low" scenario assumes modest economic growth and a focus on minimalistic housing, leading to the lowest per capita floor area expansion, and is based on the "low" energy demand (LED) scenario used in the 2021 paper; the "medium" scenario refers to SSP1; and the "high" scenario refers to SSP2 (Fishman *et al.*, 2021).

Forest sector

The wide range of activities related to sustainable forest management, the provision and production of timber and other wood and non-wood forest products, the protection of forest ecosystems and biodiversity, and safeguarding the benefits of forests. Thus, it encompasses all activities involving forests, as well as agroforestry, and diverse stakeholders, including governments, civil-society organizations, the private sector, Indigenous Peoples, vulnerable and marginalized communities, youth and women (FAO, 2024).

Nationally Determined Contributions (NDCs)

Pledges submitted by countries that formally accept or "ratify" the Paris Agreement on how they intend to address climate change (Rogelj *et al.*, 2018).

Planted forests, plantation forests

A planted forest is a forest that is created by planting or seeding trees (i.e. these trees are expected to make up more than 50 percent of the growing stock at maturity). A plantation forest is a type of intensively managed planted forest. There are three characteristics of a plantation forest: (1) one or two species, (2) even-aged, (3) regular spacing between trees (FAO, 2023b).

Roundwood

Wood in the rough that is felled or otherwise harvested and removed. It comprises all wood obtained from removals (i.e. the quantities removed from forests and from trees outside the forest), including wood recovered from natural, felling and logging losses during the period, calendar year or forest year. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form (e.g. branches, roots, stumps and burls, where these are harvested) and wood that is roughly shaped or pointed. It is an aggregate comprising woodfuel, including wood for charcoal, and industrial roundwood (FAO, 2022a).

Sawnwood

Wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness (FAO, 2022a).

Urban adoption rate (FOROM modelling scenario)

The rate of adoption of engineered wood products in building construction methods in urban development. Specifically, it is the additional share of softwood lumber demand used for building construction as a result of changes in urbanization and the corresponding demand for timber buildings.

Wood products

Wood products are manufactured wood-based materials with applications ranging from structural and non-structural building materials to paper, textiles, biochemicals and biopolymers. They are a subset of forest products, which also include woodfuel and non-wood forest products.

Wood use intensity (FOROM modelling scenario)

The amount of wood used (cubic metres) per square metre of floor space, reflecting changes in building practices and material efficiency.

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9 Appendix

9.1 FOrest Resource Outlook Model (FOROM) supplementary information

Table A1 Wood product categories represented in FOROM

Name	Description	Units
Industrial roundwood	Sawlogs and veneer logs; pulpwood, round and split; and other industrial roundwood.	m^3
Fuelwood	Roundwood that will be used as fuel for purposes such as cooking, heating or power production.	m^3
Other roundwood	Industrial roundwood (wood in the rough) other than sawlogs, veneer logs and/or pulpwood.	m^3
Sawnwood	Wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness.	m^3
Plywood	A panel consisting of an assembly of veneer sheets bonded together with the direction of the grain in alternate plies generally at right angles. Thin sheets of wood of uniform thickness, not exceeding 6 mm, rotary cut (i.e. peeled), sliced or sawn.	m^3
Particle board	A panel manufactured from small pieces of wood or other lignocellulosic materials (e.g. chips, flakes, splinters, strands, shreds, shives, etc.) bonded together by the use of an organic binder together with one or more of the following agents: heat, pressure, humidity, a catalyst, etc.). The particle board category is an aggregate category. It includes oriented strandboard (OSB), medium-density particle board, waferboard and flaxboard.	m^3
Fibreboard	A panel manufactured from fibres of wood or other lignocellulosic materials with the primary bond deriving from the felting of the fibres and their inherent adhesive properties (although bonding materials and/or additives may be added in the manufacturing process). It includes fibreboard panels that are flat-pressed and moulded fibreboard products. In the production and trade statistics, it represents the sum of hardboard, medium/high density fibreboard (MDF/HDF) and other fibreboard.	m^3

Name	Description	Units
Mechanical pulp	Wood pulp obtained by grinding or milling pulpwood or residues into fibres, or through refining chips or particles.	t
Chemical pulp	Wood pulp obtained by subjecting pulpwood, woodchips, particles or residues to a series of chemical treatments. It includes sulphate (kraft) wood pulp, soda wood pulp and sulphite wood pulp.	t
Other pulp	Pulp manufactured from recovered paper or from fibrous vegetable materials other than wood and used for the manufacture of paper, paperboard and fibreboard.	t
Newsprint	Paper mainly used for printing newspapers. It is made largely from mechanical pulp and/or recovered paper, with or without a small amount of filler.	t
Printing and writing paper	Paper, except newsprint, suitable for printing and business purposes, writing, sketching, drawing, etc. Made from a variety of pulp blends and with various finishes.	t
Other paper and paperboard	Other papers and boards for industrial and special purposes.	t
Wood pellets	Agglomerates produced either directly by compression or by the addition of a binder in a proportion not exceeding 3% by weight.	t
Chips, particles and residuals	Wood that has been reduced to small pieces and is suitable for pulping, for particle board and/or fibreboard production, for use as a fuel, or for other purposes.	m^3
Waste paper	Waste and scraps of paper or paperboard that have been collected for reuse or trade.	t

Note: Adapted from FAOSTAT definitions: https://openknowledge.fao.org/handle/20.500.14283/cb4108en.
Source: Authors' own elaboration.

Table A2 Countries and regions represented in FOROM in the current study. Each listed country is modelled individually and the rest of the countries and regions in that modelling region (Table A3) are modelled as an aggregate

Africa	Asia	Europe	Central America	North America	Oceania	South America
Nigeria	China	Austria	Rest of Central America	Canada	Australia	Argentina
South Africa	India	Belarus		Mexico	New Zealand	Brazil
Rest of Africa	Indonesia	Belgium		United States of America	Rest of Oceania	Chile
	Japan	Estonia		Rest of North America		Uruguay
	Malaysia	Finland				Rest of South America
	Myanmar	France				
	Russian Federation	Germany				
	Thailand	Latvia				
	Türkiye	Norway				
	Viet Nam	Poland				
	Rest of Asia	Portugal				
		Romania				
		Slovakia				
		Spain				
		Sweden				
		Ukraine				
		United Kingdom of Great Britain and Northern Ireland				
		Rest of Europe				

Note: For more information on FOROM, see: Johnston, C.M.T., Guo, J. and Prestemon, J.P. 2021. *The FOrest Resource Outlook Model (FOROM): A technical document supporting the Forest Service 2020 RPA Assessment*. Asheville, NC. https://research.fs.usda.gov/treesearch/62897.

Source: Authors' own elaboration.

Table A3 Countries and regions included in aggregate (e.g. Rest of Europe) for each FOROM modelling region

Africa	Asia	Europe	Central America	North America	Oceania	South America
Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Sudan, Sudan, Togo, Tunisia, Uganda, United Republic of Tanzania, Zanzibar, Zambia, Zimbabwe	Afghanistan, Armenia, Azerbaijan, Bahrain, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lao People's Democratic Republic, Lebanon, Maldives, Mongolia, Myanmar, Nepal, Oman, Pakistan, Philippines, Qatar, Republic of Korea, Saudi Arabia, Singapore, Sri Lanka, Syrian Arab Republic, Tajikistan, Timor-Leste, Turkmenistan, United Arab Emirates, Uzbekistan, Yemen	Albania, Andorra, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Faroe Islands, Georgia, Gibraltar, Greece, Greenland, Hungary, Iceland, Ireland, Italy, Liechtenstein, Lithuania, Luxembourg, Malta, Montenegro, Netherlands (Kingdom of the), North Macedonia, Republic of Moldova, Serbia, Slovenia, Switzerland	Antigua and Barbuda, Bahamas, Barbados, Belize, British Virgin Islands, Cayman Islands, Costa Rica, Cuba, Curaçao, Dominica, Dominican Republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Montserrat, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Saint Martin (French part), Trinidad and Tobago, Turks and Caicos Islands	Saint Pierre and Miquelon	American Samoa, Ascension, Saint Helena and Tristan da Cunha, British Indian Ocean Territory, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Kiribati, Marshall Islands, Micronesia (Federated States of), Nauru, New Caledonia, Niue, Norfolk Island, Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wake Island, Wallis and Futuna Islands	Aruba, Bolivia (Plurinational State of), Colombia, Ecuador, Falkland Islands (Malvinas), French Guiana, Guyana, Paraguay, Peru, Suriname, Venezuela (Bolivarian Republic of)

Source: Authors own elaboration.

9.2 Background calculations for values shown in Table 2.3 (Section 2.2.1)

Table A4 Generating comparable metrics across two studies regarding the CO_2 emission reduction potential of using engineered wood products in building construction

1. Churkina *et al.* (2020), 30 m^2 floor area per capita

Cumulative CO_2 emissions related to construction (raw materials manufacturing)

Unit: Gt CO_2	Steel and concrete	Steel and concrete (reduction compared with BAU)	Timber	Timber (reduction compared with BAU)	Total emission reductions
BAU	16		0.04		
10% timber	14.47	1.53	0.73	-0.69	**0.84**
50% timber	8.04	7.96	3.65	-3.61	**4.35**
90% timber	1.61	14.39	6.57	-6.53	**7.86**

2. Mishra *et al.* (2022)

Cumulative CO_2 emissions related to construction (raw materials manufacturing)

Unit: Gt CO_2	Steel and concrete	EWP	Total	Total emission reductions
BAU	30	0	**30**	
10% timber	24	<1	**25**	**5**
50% timber	8	4	**11**	**19**
90% timber	<1	12	**13**	**17**

Cumulative CO_2 emissions related to land use change

Unit: Gt CO_2		Emission reduction compared with BAU		
		Gt CO_2/year	cumulative	in %
BAU	-168			
10% timber		0.12	**9**	5%
50% timber		0.66	**53**	31%
90% timber		1.11	**89**	53%

Cumulative overall CO_2 emissions savings (land use and construction)

Unit: Gt CO_2		Emission reduction compared with BAU		
		Gt CO_2/year	cumulative	in %
BAU	-138			
10% timber		0.18	**14.4**	10%
50% timber		0.89	**71.2**	51%
90% timber		1.32	**105.6**	77%

Notes: All values are cumulative CO_2 emissions for the period 2020–t_{end} (unless noted differently), with t_{end} being 2050 (Churkina *et al.*, 2020) and 2100 (Mishra *et al.*, 2022), respectively. BAU = business-as-usual; EWP = engineered wood product.

Sources: Churkina, G., Organschi, A., Reyer, C.P.O., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E. and Schellnhuber, H.J. 2020. Buildings as a global carbon sink. *Nature Sustainability*, 3:269–276. https://doi.org/10.1038/s41893-019-0462-4
Mishra, A., Humpenöder, F., Churkina, G., Reyer, C.P.O., Beier, F., Bodirsky, B.L., Schellnhuber, H.J., Lotze-Campen, H. and Popp, A. 2022. Land use change and carbon emissions of a transformation to timber cities. *Nature Communications*, 13: 4889. https://doi.org/10.1038/s41467-022-32244-w.

9.3 Climate change mitigation potential: Preliminary analysis

Table A5 Substitution factor values used in the preliminary analysis in Chapter 5

Source	Description	Region	Value (source)	Unit (source)	Value
Cardinal *et al.* (2024): Figure 4	Harvested wood product end use: insulation, siding, roofing, windows	CAN	1.08	tC/tC	1.08
Hassegawa *et al.* (2022): Table S1	Nine-storey building featuring CLT panels as the main structural material, replacing reinforced concrete; life cycle stages: production, use, end-of-life (Durlinger *et al.*, 2013)	AUS	1.95	kgC/kgC	1.95
Hassegawa *et al.* (2022): Table S1	Residential building (four-storey CLT) versus replacing concrete slab with light gauge steel studded walls; life cycle stages: production, end-of-life (Grann *et al.*, 2013)	CAN	0.46 (0.38–0.56)	kgC/kgC	0.46
Hassegawa *et al.* (2022): Table S1	Multi-storey buildings (more than 8 storeys), CLT replacing reinforced concrete; life cycle stages: production, end-of-life (Hart *et al.*, 2021)	GBR	0.58	kgC/kgC	0.58
Hassegawa *et al.* (2022): Table S1	Multi-storey buildings (more than 8 storeys), CLT replacing steel; life cycle stages: production, end-of-life (Hart *et al.*, 2021)	GBR	1.02	kgC/kgC	1.02
Hassegawa *et al.* (2022): Table S1	Mid-rise urban construction (4–12 storeys), with CLT wall and floordeck, replacing concrete and steel, floorspace 9.2 m^2/cap; life cycle stage: production (Churkina *et al.*, 2020)	Global	0.16	kgC/kgC	0.16
Hassegawa *et al.* (2022): Table S1	Mid-rise urban construction (4–12 storeys), with CLT wall and floordeck, replacing concrete and steel, floorspace 30 m^2/cap; life cycle stage: production (Churkina *et al.*, 2020)	Global	0.28	kgC/kgC	0.28
Hassegawa *et al.* (2022): Table S1	Mid-rise urban construction (4–12 storeys), with CLT wall and floordeck, replacing concrete and steel, floorspace 79.1 m^2/cap; life cycle stage: production (Churkina *et al.*, 2020)	Global	0.48	kgC/kgC	0.48
Myllyviita *et al.* (2021): Table 3	Wood replacing houses with fossil raw materials (steel, concrete)	CAN	2.4	tC/tC	2.4
Myllyviita *et al.* (2021): Table 3	Sawnwood for single-family home, multi-family home and multi-use building	CAN	2.1	tC/tC	2.1

Source	Description	Region	Value (source)	Unit (source)	Value
Myllyviita *et al.* (2021): Table 3	Ceramic tile replaced with wood flooring	CHN	0.17–0.78	tC/m^3	2.07
Myllyviita *et al.* (2021): Table 3	Softwood lumber, planed and dried for building purposes	DEU	1.4	tC/tC	1.4
Myllyviita *et al.* (2021): Table 3	Softwood-based glued timber products (glulam, CLT); wood product replaces concrete, steel, bricks; life cycle stages include production and end-of-life (Hassegawa *et al.*, 2022)	DEU	1.3	tC/tC	1.3
Myllyviita *et al.* (2021): Table 3	Wooden flooring (one layer, multi layers), laminate flooring versus ceramic tiles, plastic flooring, wall-to-wall carpet	DEU	1.35	tC/tC	1.35
Myllyviita *et al.* (2021): Table 3	Doors (interior, exterior) – only framing/construction versus steel, aluminum, PVC	DEU	1.62	tC/tC	1.62
Myllyviita *et al.* (2021): Table 3	Wooden window frames versus PVC, aluminum	DEU	1.62	tC/tC	1.62
Myllyviita *et al.* (2021): Table 3	Core and shell 2030	EU-28	1.25	$kgCO_2$-eq/ kgHWP	0.341
Myllyviita *et al.* (2021): Table 3	Windows 2030	EU-28	4.42	$kgCO_2$-eq/ kgHWP	1.21
Myllyviita *et al.* (2021): Table 3	Claddings 2030	EU-28	0.72	$kgCO_2$-eq/ kgHWP	0.196
Myllyviita *et al.* (2021): Table 3	Laminates 2030	EU-28	1.22	$kgCO_2$-eq/ kgHWP	0.333
Myllyviita *et al.* (2021): Table 3	Parquets 2030	EU-28	−0.0131	$kgCO_2$-eq/ kgHWP	−0.00357
Myllyviita *et al.* (2021): Table 3	Sawnwood in construction	FIN	1.1	tC/tC	1.1
Myllyviita *et al.* (2021): Table 3	Truss and flooring; "m^3" in unit denotes volume of roundwood used as input in the production of the wood product that substitutes other materials (Petersen and Solberg. 2005. *Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden*)	FRA	0.169	Mg/m^3 of carbon eq	0.738

Source	Description	Region	Value (source)	Unit (source)	Value
Myllyviita *et al.* (2021): Table 3	Exterior cladding; "m³" in unit denotes volume of roundwood used as input in the production of the wood product that substitutes other materials (Petersen and Solberg. 2005. *Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden*)	FRA	0.024	Mg/m^3 of carbon eq	0.105
Myllyviita *et al.* (2021): Table 3	Interior coverings; "m³" in unit denotes volume of roundwood used as input in the production of the wood product that substitutes other materials (Petersen and Solberg. 2005. *Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden*)	FRA	0.024	Mg/m^3 of carbon eq	0.105
Myllyviita *et al.* (2021): Table 3	Sawnwood and plywood; substitution of wooden buildings for non-wooden buildings	JPN	301.3	kgC/m^3	1.32
Myllyviita *et al.* (2021): Table 3	Roundwood and sawnwood; substitution of wooden piles for cement and sand piles	JPN	46.8	kgC/m^3	0.204
Myllyviita *et al.* (2021): Table 3	Roundwood and sawnwood; substitution of wooden guardrails for metal guardrails	JPN	64.5	kgC/m^3	0.282
Myllyviita *et al.* (2021): Table 3	Concrete, steel to wood, houses	NZL	2.1–15	reduced emission carbon by the increase in stored carbon	8.55
Myllyviita *et al.* (2021): Table 5	Glue-laminated timber substituting primary steel	CHE	0.68	tCO_2-eq/m^3 of wood product	0.81
Myllyviita *et al.* (2021): Table 5	Glue-laminated timber substituting secondary steel	CHE	0.14	tCO_2-eq/m^3 of wood product	0.167
Myllyviita *et al.* (2021): Table 5	Sawnwood products replacing concrete	CHE	0.5	tCO_2-eq/m^3 of wood product	0.595
Myllyviita *et al.* (2021): Table 5	Sawnwood products replacing bricks	CHE	0.37	tCO_2-eq/m^3 of wood product	0.441
Myllyviita *et al.* (2021): Table 5	Sawnwood products replacing steel, chromium, secondary	CHE	1.23	tCO_2-eq/m^3 of wood product	1.46
Myllyviita *et al.* (2021): Table 5	Sawnwood products replacing steel, chromium, primary	CHE	0.41	tCO_2-eq/m^3 of wood product	0.488

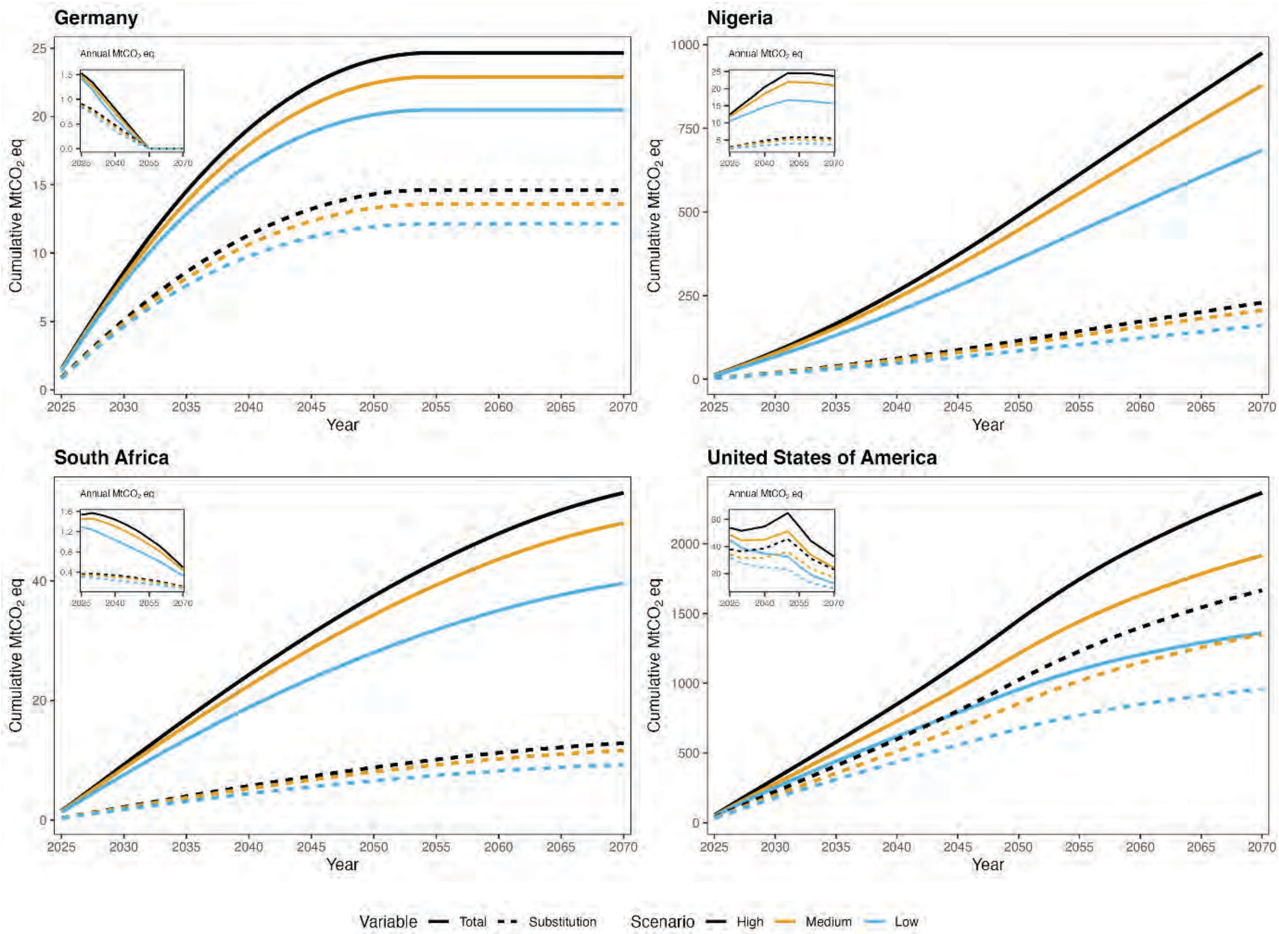
Source	Description	Region	Value (source)	Unit (source)	Value
Myllyviita *et al.* (2021): Table 5	Substitution factor for sawnwood and wood-based panels (concrete, steel substitution)	FIN	1.3	tC/tC	1.3
Myllyviita *et al.* (2021): Table 5	Sawnwood and industrial roundwood substituting fossil-fuel intensive materials, such as steel, concrete and plastics	KOR	0.04	Mg/m^3 C eq	0.0873
Sathre and O'Connor (2010): Table 2	Window frames	CAN	5 (1.2–8.8)	tC/tC	5
Sathre and O'Connor (2010): Table 2	Window frames	Europe	3.2 (1.7–4.6)	tC/tC	3.2
Sathre and O'Connor (2010): Table 2	Roof beams, wood versus steel	NOR	0.5 (−0.9–1.5)	tC/tC	0.5
Sathre and O'Connor (2010): Table 2	Flooring, wood versus stone	NOR	0.4 (−0.8–1.2)	tC/tC	0.4
Sathre and O'Connor (2010): Table 2	Flooring, wood versus alternatives	NOR	1.9 (0.1–14)	tC/tC	1.9
Sathre and O'Connor (2010): Table 2	Single-family house wood versus concrete, Atlanta	USA	2.2	tC/tC	2.2
Sathre and O'Connor (2010): Table 2	Single-family house wood versus steel, Minneapolis	USA	0.9	tC/tC	0.9
Sathre and O'Connor (2010): Table 2	Window frames	USA	5 (1.2–8.8)	tC/tC	5
Sathre and O'Connor (2010): Table 2	Single-family house wood versus concrete, Atlanta	USA	2.8 (2.8–6.6)	tC/tC	2.8
Sathre and O'Connor (2010): Table 2	Single-family house wood versus steel, Minneapolis	USA	0.4 (−0.01–2.2)	tC/tC	0.4
Sathre and O'Connor (2010): Table 2	Solid wood flooring	SWE	0.4 (0.2–0.7)	tC/tC	0.4

Source	Description	Region	Value (source)	Unit (source)	Value
Sathre and O'Connor (2010): Table 2	Wood door versus steel door	USA	3	tC/tC	3
Simonsen *et al.* (2023): Table 5	High-tech spruce CLT substituting steel bar	NOR	4.31	$kgCO_2$-eq/ kgHWP	2.35

Notes: The table outlines the source, description of product, region, original values and units as reported in the source, and derived values in tC/tC. To convert the original values to the derived values, values for sawnwood density and carbon conversion are 0.458 Mg/m^3 and 0.229 MgC/m^3, respectively, taken from IPCC (2014). CLT = cross-laminated timber; glulam = glue-laminated timber; HWP = harvested wood product; PVC = polyvinyl chloride. Region codes: AUS = Australia; CAN = Canada; CHE = Switzerland; CHN = China; DEU = Germany; EU-28 = 27 Member States of the European Union and the United Kingdom of Great Britain and Northern Ireland; FIN = Finland; FRA = France; GBR = United Kingdom of Great Britain and Northern Ireland; JPN = Japan; KOR = Republic of Korea; NOR = Norway; NZL = New Zealand; SWE = Sweden; USA = United States of America.

Sources: Cardinal, T., Alexandre, C., Elliot, T., Kouchaki-Penchah, H. and Levasseur, A. 2024. Climate change substitution factors for Canadian forest-based products and bioenergy. *Ecological Indicators*, 160: 111940. https://doi.org/10.1016/j.ecolind.2024.111940 Hassegawa, M., Van Brusselen, J., Cramm, M. and Verkerk, P.J. 2022. Wood-based products in the circular bioeconomy: Status and opportunities towards environmental sustainability. *Land* (Basel), 11(12):2131. https://doi.org/10.3390/land11122131 Myllyviita, T., Soimakallio, S., Judl, J. and Seppälä, J. 2021. Wood substitution potential in greenhouse gas emission reduction–review on current state and application of displacement factors. *Forest Ecosystems*, 8: 42. https://doi.org/10.1186/s40663-021-00326-8 Sathre, R. and O'Connor, J. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science and Policy*, 13: 104–114. https://doi.org/10.1016/j.envsci.2009.12.005 Simonsen, M., Kjønaas, O.J. and Aall, C. 2023. Substitution of fossil-energy intensive building materials by wood products – Does it matter? A case study from Western Norway. *Journal of Cleaner Production*, 383: 134941. https://doi.org/10.1016/j.jclepro.2022.134941.

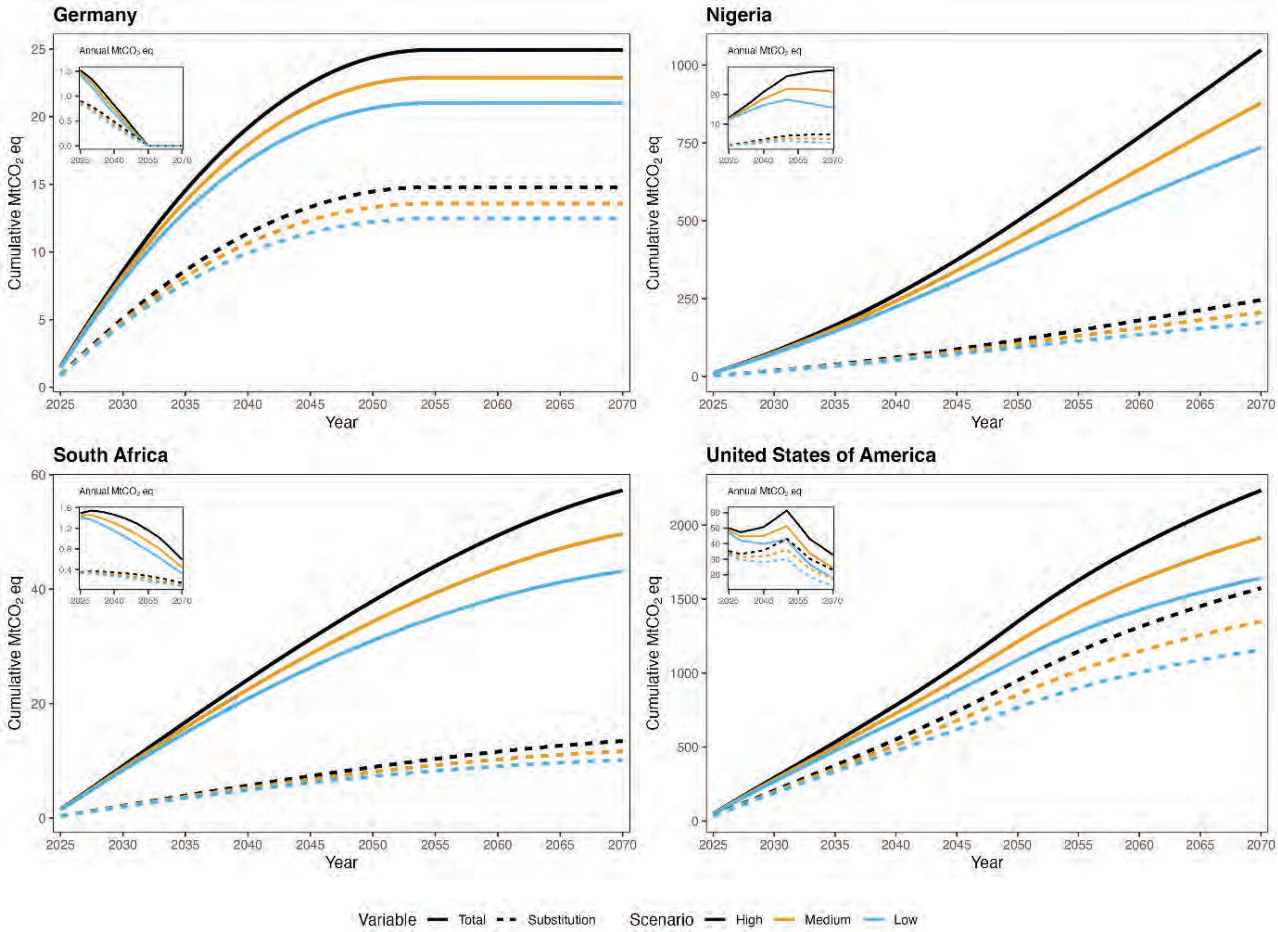
Figure A1 Country-level cumulative and annual emission reductions for four case study countries, resulting from additional engineered wood product demand for floor area per capita scenarios



Notes: The emission reductions shown include a breakdown of contribution via substitution effects. The additional emission reductions per year are shown in the inset plots.

Source: Authors' own elaboration.

Figure A2 Country-level cumulative and annual emission reductions for four case study countries, resulting from additional engineered wood product demand for wood use intensity scenarios



Notes: The emission reductions shown include a breakdown of contribution via substitution effects. The additional emission reductions per year are shown in the inset plots.

Source: Authors' own elaboration.

9.4 Forest products in the bioeconomy: Review of market trends, demand drivers, limitation to market growth, and trade-offs with other products

9.4.1 Building and construction

This section provides an analysis of the current market status of engineered wood products (EWPs), important drivers of demand, limitations of market growth, and the trade-offs of focusing on EWPs with respect to other kinds of forest products.

Unlike traditional sawnwood, which exhibits variability in strength and dimensional stability, the controlled manufacturing process of EWPs ensures greater uniformity in mechanical properties, making it competitive in load-bearing applications. EWPs offer high strength-to-weight ratios, seismic resilience and predictable load-bearing capacities that are comparable to steel and reinforced concrete (Stark and Cai, 2021; Abed *et al.*, 2022). Because tree growth involves the absorption of atmospheric carbon dioxide, wood is a significant medium of carbon storage, and as a result, the use of EWPs in construction is an effective way to transfer stored carbon into urban environments. Several studies have suggested that broad adoption of EWPs for mid-rise and high-rise construction could lock away substantial amounts of carbon for decades (Churkina *et al.*, 2020; Himes and Busby, 2020; D'Amico *et al.*, 2021). Churkina *et al.* (2020) found that the amount of carbon stored in EWP buildings in the future could range from 2 to up to 20 Gt over a 30-year period depending on the levels of global adoption of EWPs. EWP systems therefore offer a viable path towards decarbonizing the construction industry through the combination of carbon storage and the substitution effect of avoiding conventional materials such as concrete, cement and steel (D'Amico *et al.*, 2021).

Fully realizing the carbon storage and substitution benefits of EWPs will depend on robust sustainable forest management, including carefully regulated harvests, protection of agricultural land for food production, close monitoring of supply chains to prevent deforestation, and the application of advanced silvicultural methods to minimize harvest losses and conserve biodiversity (Mishra *et al.*, 2022; Pomponi *et al.*, 2020). To achieve large-scale implementation, governments and industry stakeholders will need to update building codes to acknowledge the fire resistance (Mitchell *et al.*, 2023) and other relevant structural properties of EWPs, invest in retraining construction workforces, and expand markets and manufacturing of timber products to valorize residues and waste streams. Additionally, planning for the end-of-life phase of EWP constructions will be crucial: designing buildings for disassembly, reusing or recycling timber components, and using waste wood as fuel only after multiple cascading uses will enhance their climate benefits. (Abed *et al.*, 2022; Ramage *et al.*, 2017).

Box A1. Wood-based composites

Wood-based composites can be grouped into (Stark and Cai, 2021):

- veneer-based materials, inc. plywood, laminated veneer lumber (LVL), parallel-strand lumber
- laminates, incl. glue-laminated timber (glulam)
- composite materials, incl. fibreboard, particle board, laminated or oriented strand lumber
- wood–nonwood composites.

Glulam, cross-laminated timber (CLT), LVL, and other structural engineered wood products (EWPs) are able to take on advanced properties (increased fire resistance, greater strength, higher durability) depending on the kinds of wood, adhesive, and processing techniques used (Stark and Cai, 2021).

Source: Stark and Cai. 2021. Chapter 11: Wood-based composite materials: Panel products, glued laminated timber, structural composite lumber, and wood–nonwood composites. In: Wood handbook - wood as an engineering material. General Technical Report FPL-GTR-282. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 29 pp. https://research.fs.usda.gov/treesearch/62258.

Market trends

Glulam, the first widely used structural EWP, dates back to the early 1900s, patented by a German inventor for straight beams in 1901 and for curved sections in 1906 (Rhude, 1996). The development of CLT was accelerated in Austria in the early 1990s (Brandner *et al.*, 2016) and proved to be a game changer for the building industry, when combinations of glulam and CLT were allowed for the timber-based construction of mid-rise buildings as a viable alternative to the then dominant mineral-based steel, concrete and brick structures. CLT's perpendicularly arranged layers of solid-sawn timber provide high dimensional in-plane stability (Brandner *et al.*, 2016), making it a viable material for building floors, in addition to wall systems.

European Union (EU-27) countries are leading producers of EWPs, with Austria, France and Germany producing 82 percent of global CLT output (FAOSTAT, 2025). Japan is a major producer of glulam (approx 22.5 percent of global production alone), and together with Austria and Germany, the top three producers contribute 67 percent of global glulam (FAOSTAT, 2025). North American production is steadily growing, supported by interest from the forest industry. In 2023, North America produced about 1.9 million m^3 of LVL, 370 000 m^3 of glulam and 50 000 m^3 of CLT (FAOSTAT, 2025). EWP production capacity in the United States was estimated at 1.767 million m^3 in 2022, indicating a large potential to expand manufacturing within the country (Atkins *et al.*, 2023).

Industrialized countries in the Asia-Pacific region are also in the process of rapidly scaling up their manufacturing capacities (Beck-O'Brien *et al.*, 2022). Japan, which has a long history of wood-based construction, began CLT production in 2011. In 2023, Japan produced 1.59 million m^3 of glulam and 18 000 m^3 of CLT (FAOSTAT, 2025). The technology is being widely promoted, and infrastructure and forestry agencies in Japan have indicated that CLT production capacity could reach 500 000 m^3 by 2024 (Liu *et al.*, 2023). Australia, China and New Zealand have similarly expanded production of CLT and other EWPs in recent years, but official estimates are difficult to extrapolate as most countries do not account for EWPs as a separate category of wood products.

Even with the rapid growth of EWP output in North America and the Asia-Pacific, it is unclear whether global EWP production can reach the levels required for significant transformation of the construction sector. Within the EU-27 and the United Kingdom, where the annual production capacity of EWPs was estimated at 7.4 million m^3 in 2023, annual demand is projected to reach 33 million m^3 by 2030, assuming a 50 percent adoption rate of biobased construction materials (Haisma *et al.*, 2023). Taking the construction sector globally, it has been estimated that supplying the EWP equivalent of even 0.1 percent of the total concrete sector by mass would require 40 million m^3 of EWPs, highlighting the challenge of meeting carbon substitution goals in construction through EPWs (Beck-O'Brien *et al.*, 2022).

Presently, the United States and Europe collectively consume over 80 percent of EWP production. It is worth noting, however, that global consumption patterns could shift significantly with increasing levels of awareness and product satisfaction. For example, in their "Optimistic" and "Extreme" demand scenarios for EWP, Nepal *et al.* (2021) found that China would account for 38 and 62 percent of global demand by 2060, respectively. This indicates that supply chains may also have to be restructured to meet new and increasing sources of demand.

Drivers of demand

Recent technological advancements in EWPs are driving wider adoption at the global scale. Innovations in material science, adhesive formulations and precision manufacturing have substantially improved the structural capabilities of mass timber, enabling its application in mid- and high-rise buildings. In particular, prefabricated EWP construction has emerged as a notable approach, offering reduced material waste, reduced emissions from transport, improved cost-effectiveness, and shortened installation timelines (Abed *et al.*, 2022; Tupėnaitė *et al*., 2023; Harte, 2017). EWPs, which have low thermal conductivity, have been found to improve the energy efficiency of buildings (Abed *et al.*, 2022). In parallel, increased awareness, availability and acceptance of mass timber across industry stakeholders have spurred broader market uptake (Mallo and Espinoza, 2016). Regulatory changes have further accelerated this trend: as of the 2021 edition, the International Building Code permits mass timber structures up to 18 storeys, opening a significant new arena for EWP applications and solidifying their role in future construction projects (Kumar *et al.*, 2024).

A key driver for the expanding use of EWPs globally is the growing focus on sustainability and climate action in the construction sector. Governments and industry stakeholders are increasingly looking for ways to reduce embodied carbon emissions, spurring material substitution trends that favor biobased products over steel and concrete. Because EWPs rely on renewable, forest-sourced feedstocks, they align with bioeconomy policy directives aimed at producing high-value, biobased materials (FAO, 2022; Hurmekoski *et al.*, 2018). In addition, EWPs help diversify and expand value creation in forest-based economies, creating employment opportunities and fostering industrial innovation (Hurmekoski *et al.*, 2018). Finally, urbanization remains a key driver of global construction activity, which in turn fuels demand for building materials, including mass timber. The shift towards denser urban living, especially in Africa and Asia, will necessitate the construction of multi-storey residential and mixed-use buildings that can now be built with more sustainable materials (Verkerk *et al.*, 2022; Harte, 2017). Given that EWPs have been deemed suitable for high-rise building construction, it presents an attractive solution for sustainable urban development (Kumar *et al.*, 2024).

The adoption of EWP construction could be further accelerated through supporting policies and market incentives for producers, architects, designers and end users. Social perceptions of timber as a construction material have been found to affect consumer preferences. Certification schemes and advanced training could address public and institutional concerns around the economic, environmental and technical performance of timber and EWPs (Hildebrandt *et al.*, 2017).

Limitations to market growth

Softwood species like pine (*Pinus* spp.), spruce (*Picea* spp.) and fir (*Abies* spp.) currently dominate the mass timber market. Hardwood species are being explored worldwide, particularly beech (*Fagus* spp.) (Aicher *et al.*, 2016a, b), oak (*Quercus* spp.) and maple (*Acer* spp.) (Hassler *et al.*, 2024) in Europe, and *Eucalyptus* spp. in Australia and South America (Baño *et al.*, 2025). Increasing production and use of EWPs will drive increased use of softwood until pathways to produce mass timber from hardwood are established. Nepal *et al*. (2021) forecast that by 2060, increased adoption of EWPs could drive additional annual demand for softwood lumber by 8, 23 and 53 million m^3 under conservative, optimistic and extreme scenarios, respectively. The low conversion efficiency of timber to EWPs further intensifies demand in roundwood and raises concerns about exceeding sustainable production thresholds (Pramreiter *et al.*, 2023a, b; Beck-O'Brien *et al.*, 2022). Meeting higher demand for timber through intensified harvesting and expansion of forest areas may compromise forest integrity and biodiversity, especially in regions with weak forest sector governance. Countries with established forest industries, such as the Nordic European countries, Canada, and parts of the United States, may be able to more readily integrate EWPs into urban development, whereas countries with less developed forest industries, including parts of Africa and Asia, may face supply constraints and bottlenecks in sawmill and processing capacity (Ramage *et al.*, 2017). Latin American countries, with relatively strong forest industries, report lack of certification, regulations and technical knowledge as key limitations to expanding wood-based construction in the region (Araya *et al.*, 2022). Regional variations in construction practices and resource availability will also determine the scalability of EWPs. Production processes have so far been optimized for softwood, which is dominant in Europe and North America, yet climate change is altering forest conditions and species availability. At the same time, forests and markets in Africa, Asia and South America may gain an advantage by leveraging hardwood timber for EWPs. Further research into improved structural design and diverse raw material selection is required to operationalize EWPs as a global solution to construction demands (Pramreiter *et al.*, 2023a; Lauri *et al.*, 2021).

A key limitation on EWP market growth is the slow adaptation of local and regional building codes, especially in areas without a strong tradition of wood construction. In contrast, regions such as parts of Europe, Japan and North America, where wood construction has historically been more common, have more established codes supporting EWP use (Brandt *et al.*, 2021; Firoozi *et al.*, 2024). Several studies have found the cost of EWP construction to be comparable with conventional construction; however, all of these studies were located in countries with industrialized economies and high labour costs (Sorathiya, 2019; Gu *et al.*, 2020; Andersen *et al.*, 2023). In emerging markets across Africa and Asia, establishing infrastructure for the manufacture of EWPs will face challenges such as access to capital, the need to train specialized labour, and supply chain bottlenecks, which hamper regular material input (Verkerk *et al.*, 2022; Firoozi *et al.*, 2024). Market acceptance also remains constrained by a risk-averse construction sector, where deeply entrenched norms and long-term investment cycles discourage swift transitions (Hurmekoski *et al.*, 2018; Abed *et al.*, 2022).

Trade-offs with other forest products

Increased production of EWPs will likely divert sawnwood from traditional markets and uses. CLT and glulam have so far been manufactured with high-quality softwood timber, typically sourced from spruce, fir and pine species, which are also the primary inputs for conventional structural timber and furniture manufacturing. As sawmills prioritize EWP-grade timber, the availability of lower-grade timber for conventional construction may decrease, potentially driving up prices of softwood (Nepal *et al.*, 2021). Increased demand for sawnwood could also result in regions like Europe becoming importers of coniferous sawnwood, impacting global trade of wood products. An increase in EWP manufacturing would also boost the production of wood-based panels such as particle board and oriented strandboard (OSB) in well-developed timber industries as a result of increased residues from sawmilling (Jonsson *et al.*, 2021).

Primary processing of sawnwood produces 30 to 60 percent of the raw material as waste, depending on species of wood and technology used (FAO, ITTO and United Nations, 2020). Data on additional residues produced during the manufacture of EWPs are not readily available, however, as with any manufacturing process, it is likely that a substantial stream of waste will be generated. For instance, Churkina *et al.* (2020) assume that 50 percent of timber is produced as residue in the production of EWPs. These residues will, therefore, represent an additional resource stream available for valorization.

Residues from primary processing are typically fed into *in situ* bioenergy generation processes or used as feedstock for manufacturing pulp and pulp-derived products. Resnais *et al.* (2021) analysed residues from CLT production and found the residues of larger dimensions to be suitable for the creation of new construction materials, which could improve the manufacturing efficiency of EWPs. Smaller dimension residues could potentially feed into existing bioenergy or pulp product supply chains. However, this is highly dependent on the proximity of pulp manufacturers with EWP manufacturers, and the success of leveraging this additional feedstock depends on supply chain logistics and the technologies used across manufacturing sites (Hurmekoski *et al.*, 2018).

9.4.2 Paper and packaging

Paper production consists of three key stages: (1) pulping, (2) bleaching and (3) papermaking (or finishing), with wood, composed of cellulose, hemicellulose and lignin, as a primary raw material. Woody biomass used for paper production generally utilizes softwoods like pine, spruce and fir, as well as hardwoods such as eucalyptus, maple and aspen (*Populus* spp.). However, growing demand for paper and environmental concerns have led to the use of alternatives like rice (*Oryza* spp.) straw and recycled paper, as well as the introduction of more sustainable biological pulping techniques. Mechanical pulping, typically used to produce newsprint, involves grinding and refining wood into fibres, preserving more material but requiring high energy. Chemical pulping relies on heat and chemicals to dissolve lignin, resulting in stronger, higher-quality pulp that is used to produce graphic papers (Mboowa, 2024). Since 2004, historical wood pulp derived products such as newsprint and graphic paper are experiencing stark declines in production, largely due to digitalization and global internet adoption (Johnston, 2016; Verkerk *et al.*, 2022). However, sanitary papers, which include tissues, toilet paper and personal care products, and wrapping and packaging papers are gaining significance within the paper production industry, resulting in an overall increase in global pulp consumption year on year.

The paper industry, one of the largest industrial sectors in the world, is undergoing significant transformations. It is responding to contracting demand in some of its key sectors by shifting production to new and specialized paper products, while exploring increased value addition through the valorization of by-products from manufacturing. It is also contending with competition from new production regions, rising costs and regulations, and demand for innovative fibre-based products from new demographic groups. These transformations will require paper and pulp producers to manage intermediate uncertainties and turbulences, while supply chains, labour and production processes adapt to new conditions. A possible outcome of shifting production capacities and innovation in manufacturing could be that historical pulp and paper industries in North America and Europe focus on specialty and niche papers on smaller scales, while large-scale manufacturing shifts to regions with lower operational costs and growing domestic markets (Berg and Lingqvist, 2017).

Market trends

China and the United States were the top producers of paper and paperboard in 2023, with outputs of 134 million tonnes and 61 million tonnes, respectively, accounting for 48 percent of global production. Other major producers included Japan (22 Mt), Germany (19 Mt) and India (17 Mt), collectively representing an additional 15 percent of global output (FAOSTAT, 2024). The production of graphic paper and newsprint, historically significant outputs from this industry, is declining. Johnston (2016) modelled the projected decline in graphic paper consumption based on global internet adoption rates, predicting a 32 to 42 percent decline in graphic paper demand and a 48 to 68 percent reduction in newsprint demand by 2050, across scenarios regarding the rate of internet adoption. In line with these predictions, North America saw declines in newsprint production since 1992 and Europe since 2006, while graphic paper has declined in both these regions since the early 2000s (FAOSTAT, 2024; UNECE and FAO, 2024). Production of graphic paper in Asia rose sharply from 1980, and stabilized in 2012 (FAOSTAT, 2024), potentially due to lower production costs and the advantage of serving a growing domestic market in the region.

Growth in the paper industry has been unevenly distributed across traditional and new producing regions, as well as in terms of production portfolios. Production capacities have shifted from graphic paper and newsprint towards packaging and sanitary paper, with approximately 75 percent of global paper production being used for wrapping paper, case materials, cartonboard, packaging and personal care products (FAOSTAT, 2024). Demand for packaging materials and sanitary products are tied to population and gross domestic product (GDP) growth and will likely increase in the coming decades (Hurmekoski *et al.*, 2022a). This restructuring of the industry is driving innovation and specialization, however the inflow of capacity from traditional paper production lines could lead to imbalanced growth in some sectors. Increasing market pulp production in Brazil and Chile and paper production in Southeast and East Asia is competing with European and North American production (Berg and Lingqvist, 2017). China, whose imports of pulp have almost doubled from 16 million tonnes in 2013 to 29 million tonnes in 2023, will likely shape future market trends within this industry (FAOSTAT, 2024; UNECE and FAO, 2024; Berg and Lingqvist, 2017). Despite declines in key segments, the paper and pulp industry is projected to continue its growth, with significant shifts towards innovative products within and outside the sector.

Drivers of demand

Macroeconomic trends – including high inflation, increased interest rates and rising raw material and logistics costs – have reduced overall paper consumption, particularly in North America and Europe, but several key drivers continue to shape demand in the pulp and paper industry (CEPI, 2023a; Berg and Lingqvist, 2017). Digitalization and the global shift to electronic communications have accelerated the decline of newsprint and graphic papers, although this trend is less pronounced in Asian, African and South American markets (Johnston, 2016; Verkerk *et al.*, 2022). A key driver is the decline in advertising budgets for print media (UNECE and FAO, 2024). In Europe, for example, the share of advertising expenditure on print media fell from 57 percent in 1998 to just 9 percent in 2014 (Turlais, 2016). The growth of e-commerce, fuelled in part by the COVID-19 pandemic, has increased demand for packaging papers. This has been compounded by growing populations, urbanization and rising household incomes in emerging markets such as Asia and Latin America, which have driven demand for hygiene and packaging products (Verkerk *et al.*, 2022; Hurmekoski *et al.*, 2022a). These factors have resulted in an overall increase in pulp consumption despite a significant shift in traditional end uses.

Driven by mounting regulatory and consumer pressures to reduce plastic usage, the pulp and paper industry has increasingly positioned packaging products as a sustainable alternative, particularly within the food and beverage sector (Hurmekoski *et al.*, 2018; Thapliyal *et al.*, 2024). Despite Europe's apparent paper and paperboard consumption plunging by 15.3 percent in 2023, the packaging and sanitary paper segments have proven resilient. To address high costs and contracting demand, the European paper industry has strategically shifted towards more profitable and viable markets. Part of this success is due to high recycling rates, with 70 percent of raw materials derived from recovered fibres, and continuous innovation in specialty papers, barrier technologies and process efficiency (CEPI, 2023b; Berg and Lingqvist, 2017).

Limitations to market growth

The pulp and paper industry is one of the largest in the world and consumes 33 to 40 percent of global industrial roundwood production. This implies that supply of feedstocks to the industry is limited by sustainable biomass growth through forest management, and that shifts in the supply chain could have wide-reaching impacts on other industries (Beck-O'Brien *et al.*, 2022). Although the use of recycled fibres partially offsets this limitation, recycling is itself an energy-intensive process, and reliance on recovered fibres introduces challenges related to quality degradation, fibre loss after multiple recycling cycles, and contamination issues, requiring advancements in sorting and processing technologies. Additionally, the global paper recycling rate was estimated at nearly 58 percent, with some North American and European countries achieving recovery rates exceeding 80 percent. This indicates that recycled fibre could also have limited effectiveness in increasing feedstocks for paper production (Rajan *et al.*, 2024; Beck-O'Brien *et al.*, 2022).

The structure of regional paper industries plays an important role in their competitiveness. Where pulp mills are integrated with managed forest resources and paper production, energy demand is lower, and by-products can be valorized on site. The industry is the fourth largest industrial energy user, with chemical pulping, black liquor evaporation, and drying demanding significant energy (Furszyfer Del Rio *et al.*, 2022). Rising costs for energy are therefore a key limitation to the market. Innovation in energy consumption, resource use and product portfolios are, accordingly, essential to ensure competitiveness and sustained growth in the paper sector (UNECE and FAO, 2024; Furszyfer Del Rio *et al.*, 2022).

Although paper is considered a sustainable alternative to other materials, it is capital-, energy- and water-intensive, and can be a driver of unsustainable forest management (Furszyfer Del Rio *et al.*, 2022). Increased sustainability measures within production processes and supply chains are now being driven by both consumer pressure and evolving regulations. For example, the European Union Deforestation Regulation will apply to large and medium-sized operators from December 2026, with a further extension for micro and small enterprises until June 2027 (European Commission, 2025). While recent revisions excluded certain finished printed products such as books and newspaper from the regulation's scope, the wood and pulp commodities used in paper production remain strictly regulated to ensure they are deforestation-free. This will increase compliance costs, potentially limiting access of international exporters who do not meet these new standards. Global attention towards biodiversity conservation and efficient biomass usage could require industries to adapt to changing feedstocks, such as non-woody biomass, certified woody biomass, and an increasing proportion of recycled fibres (Rajan *et al.*, 2024).

Trade-offs

The transition from traditional pulp and paper production to innovative wood-based products involves a series of trade-offs tied to both market opportunities and feedstock availability. Declining graphic paper production is a key driver of innovation towards biorefineries that process lignocellulosic feedstocks. Chemical pulp serves as a critical feedstock for paper production as well as emerging wood-based products such as bioplastics, biotextiles and biochemicals. One key sector that could compete with the paper and pulp industry is wood fibre-based textiles, such as Lyocell and modal, which offer sustainable alternatives to cotton and synthetic fibres. The global demand for these textiles is projected to rise significantly, driven by increasing consumer awareness of environmental impacts and regulatory pressure to reduce reliance on fossil fuel-based materials (Hurmekoski *et al.*, 2018; Rajan *et al.*, 2024). Similarly, bioplastics derived from cellulose are gaining traction as sustainable alternatives to petroleum-based plastics, particularly in packaging applications. The global market for bioplastics is expected to almost double in the next 5 years (European Bioplastics, 2024), further driving demand for high-purity cellulose from chemical pulp (Hurmekoski *et al.*, 2018).

Shifts in paper production supply chains or increased demand for innovative wood-based products will therefore intensify competition for roundwood, sawmilling residues and industrial by-products (Hurmekoski *et al.*, 2018). A decline in graphic paper production is projected to reduce roundwood demand by an estimated 133 million m^3 by 2030 (FAO, 2024). However, the increased availability of chemical pulp is being claimed by growing demand for sanitary and packaging papers. These new supply chain dynamics could lead to fluctuations in the price of raw materials and constrain fibre availability for established paperboard and tissue sectors (Toppinen *et al.*, 2017; Rajan *et al.*, 2024).

On one hand, innovative wood-based forest products – such as lignin-based adhesives, biobased textiles and advanced biofuels – promise to broaden revenue streams, reduce carbon footprints, and respond to changing consumer demands (Toppinen *et al.*, 2017; Rajan *et al.*, 2024). On the other hand, repurposing pulp mills as biorefineries is capital intensive, time consuming and risky (Rajan *et al.*, 2024). The pulp and paper industry, and its core source of feedstocks (i.e. managed forests), are both characterized by long investment cycles, with willingness to invest dampened by the lengthy timelines and historically poor returns (Furszyfer Del Rio *et al.*, 2022; Berg and Lingqvist, 2017).

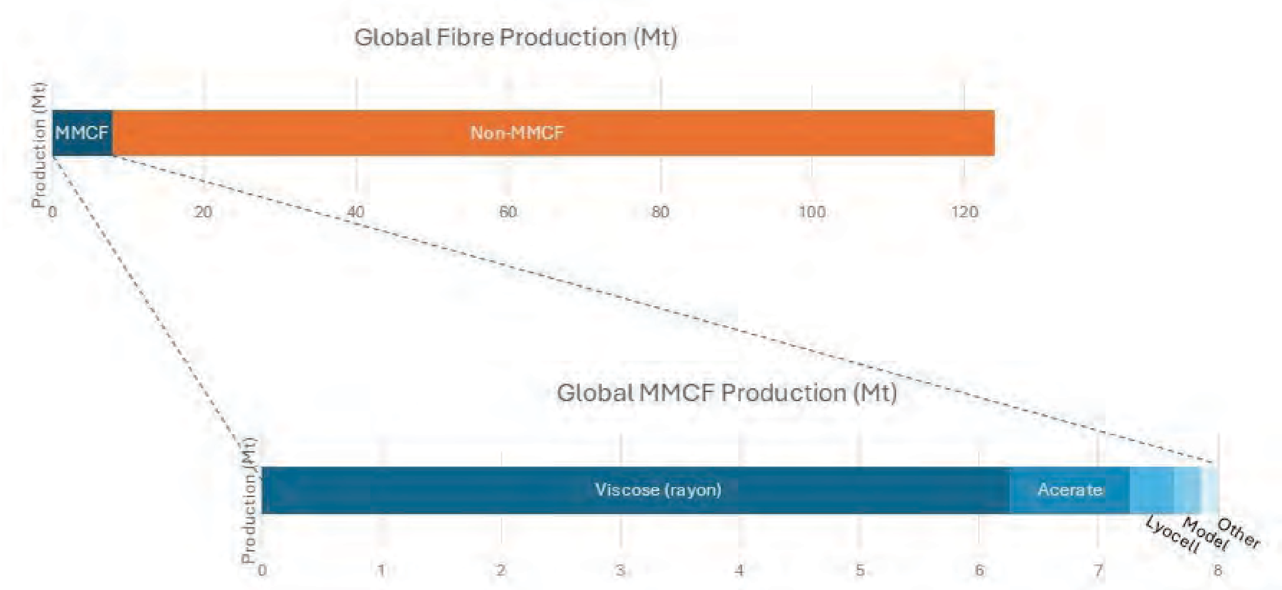
A trend so far has been the development of "swing mills", which alternately produce paper pulp and textile-grade pulp, in response to shifts in the market, where textile-grade pulp mills effectively operate as biorefineries. Flexible strategies like this highlight the imperative for integrated biorefinery models that maximize resource efficiency. Innovations in pulping efficiency, enhanced recycling technologies, and the development of alternative cellulose sources, such as agricultural residues or microbial cellulose, could help balance competing demands for pulp in both traditional and emerging applications. Yet, the sector's ability to effectively manage the trade-off between traditional pulp and paper operations, new and emerging packaging products, and the expansion of advanced wood-based products will determine its ability to balance shifting supply chains with new growth opportunities in the medium and long term (Toppinen *et al.*, 2017; Hurmekoski, 2018; Rajan *et al.*, 2024).

9.4.3 Textiles

Textile fibres can be broadly classified into natural and man-made fibres. Natural fibres are sourced from animals (silk, wool) or plants (cotton, hemp, flax, etc.), while man-made fibres are made with natural cellulose (e.g. viscose) or synthetic (polyester, nylon) fibres. Global fibre production in 2023 reached 124 million tonnes, dominated by polyester (57 percent), cotton (20 percent) and nylon (polyamide, 5 percent), with the group of man-made cellulosic fibres (MMCFs) accounting for a combined 6 percent or 7.9 million tonnes (Textile Exchange, 2024).

MMCFs are traditionally made from wood-based fibres and include viscose (80 percent market share), acetate (primarily used in non-textile applications), Lyocell and modal (both rapidly gaining market shares), as well as cupro (Figure A3; Textile Exchange, 2024).

Figure A3 Global market share of man-made cellulosic fibre in 2023 and by type



Note: MMCF = man-made cellulosic fibre.
Source: Figure created from data available in Textile Exchange (2024).

MMCFs are unique in their low environmental impact and abundant renewable feedstock availability when compared with other fibres: polyesters are based on fossil feedstocks, release microplastics during their use (Lei *et al.*, 2024), and are rarely recycled, though recent advances in chemical recycling offer pathways for greening polyester recycling (El Darai *et al.*, 2024). Cotton's environmental impacts include land use, water use, ecotoxicity, eutrophication and greenhouse gas (GHG) emissions, with substantial regional differences as to the most relevant impact category (Zhang *et al.*, 2023). In contrast, MMCFs are based on cellulose, a widely available biobased feedstock. The cellulose is modified to dissolving grade pulp (a highly pure cellulose) that serves as feedstock for cellulose derivatives and regenerated fibres (Quintana *et al.*, 2024). Cellulose sources include dissolving wood pulp for viscose, agricultural by-products, paper and cardboard, and used textiles (Frazier *et al.*, 2024). Beneficial characteristics of MMCFs are their biodegradability and their uniform morphological, mechanical and physical properties, which sets them apart from both synthetic and natural fibres (Felgueiras *et al.*, 2021). For viscose/polyamide textile blends, biochemical recycling by enzymes offers an environmentally friendly recycling option that allows full circular application of resources (Mihalyi *et al.*, 2024). Yet, like for all textile fibres, recycling of MMCFs is still in its infancy.

Among MMCFs, the most promising fibre is Lyocell, a new wood-based textile fibre with a substantially lower environmental profile than viscose. Viscose production is characterized by its high use of chemicals (sodium hydroxide and carbon disulfide) and high energy consumption, unless the viscose fibre plant is integrated with a pulp mill (Shen *et al.*, 2010). Lyocell production requires less energy and directly dissolves cellulose, reducing the use of chemicals by ten times compared with the viscose process (Felgueiras *et al.*, 2021). Innovations include using a direct non-toxic solvent like ionic liquids, no solvent at all, and bacterial nanocellulose as feedstock; also making Lyocell easier to recycle (Felgueiras *et al.*, 2021; Balkissoon *et al.*, 2023). Lyocell fibres are stronger than viscose but they are less resistant to changes in shape. While novel wood-based textiles can be modified to have properties that allow them to compete with both natural and synthetic fibres, they are not currently a perfect substitute (Orfanidou *et al.*, 2023; Hurmekoski *et al.*, 2018). Yet, some substitution of cotton with MMCFs is expected (Felgueiras *et al.*, 2021), offering MMCFs the prospect of substantial growth in the future.

Within MMCFs, Lyocell is expected to increasingly substitute for viscose, and to some extent also substitute cotton and polyester (Hurmekoski *et al.*, 2022b). Investments in innovation and scaling are needed to close the price gap between natural fibres and MMCFs, of particular relevance for Lyocell, which is still early on its path from research to market (Dharwadkar and Hautamäki, 2024). Equally important to technological advances is a shift in mindset in product design by acknowledging the specific properties of new wood-based textile fibres when selecting a fibre for a given application (Orfanidou *et al.*, 2023).

Although global efforts to reduce overall textile consumption and increase recycling are ongoing, demand for fibres continues to climb, projecting steady rises in cotton use, and even higher growth rates for other fibre categories (Textile Exchange, 2024). Within this dynamic, MMCFs can alleviate some of the environmental burden associated with increased textile consumption, provided they maintain a competitive edge against other forest sector uses of wood (Kallio, 2021).

Scaling MMCFs needs to be based on a sustainable supply of cellulosic feedstocks, with the optimum type of feedstock depending on the region. Beyond wood, alternative feedstocks exist for MMCFs and are technically viable. In the United States, widely available wood alternatives suitable for conventional conversion are residues from soybeans (*Glycine max*), wheat (*Triticum* spp.), rice, sorghum (*Sorghum* spp.), and sugarcane (*Saccharum officinarum*) (Frazier *et al.*, 2024). The proximity or, ideally, integration between feedstock source and fibre production will ensure techno-economic feasibility for scaling the technology while minimizing environmental impact as demonstrated for MMCF feedstocks of agricultural (Frazier *et al.*, 2024) and wood pulp (Shen *et al.*, 2010) origin (highlighting the substantially lower energy requirements in viscose production in an integrated facility in Austria compared with a non-integrated facility in China). By 2023, around 60 percent of wooden MMCF feedstocks came from Forest Stewardship Council (FSC) and/or Programme for the Endorsement of Forest Certification (PEFC) certified forests (Textile Exchange, 2024), indicating a strong commitment by producers to sustainable sourcing.

Market trends

The Asia-Pacific region dominates global MMCF production, with China and Indonesia's large-scale dissolving pulp mills catering to growing domestic and export-oriented markets. While Europe emphasizes high-value fibres like Lyocell and modal, North America remains a major producer and supplier of dissolving pulp. MMCF output has more than doubled since 1990 and continues to grow. China leads through extensive infrastructure and new installations, compensating for stagnation in Europe and North America due to stricter environmental regulations. Lyocell production, driven by manufacturers like Lenzing AG, Grasim Industries and Sateri, is also expanding rapidly (Dharwadkar and Hautamäki, 2024; Hummel and Määttänen, 2024). Kallio (2021) modelled projections for production and investments in wood-based textile pulps and found that by 2035, additional MMCF capacity is expected worldwide, largely through converting existing paper pulp mills to textile pulp. In lower-demand scenarios, all new capacity stems from mill conversions, whereas higher-demand scenarios prompt greenfield investments in Brazil, Chile, Indonesia and the United States (Kallio, 2021), demonstrating the link between MMCFs and paper pulp producing regions.

Regional market dynamics further contribute to the upward trajectory of MMCFs. The Asia-Pacific region, notably China, India and Indonesia, functions as a major manufacturing hub for nonwoven fabrics and textile products, thanks to an ample, cost-effective labour force and high demand for hygiene products like diapers. While Europe and North America emphasize sustainability, driving stringent regulations that slow viscose output, ongoing investments in mill conversions and greenfield facilities are accelerating MMCF production elsewhere, particularly in Brazil and Southeast Asia. Consumer preferences also play a role; in the Asia-Pacific, functionality often outweighs sustainability concerns, contrasting with Western markets where regulatory pressures and eco-consciousness drive greener fibre choices (Dharwadkar and Hautamäki, 2024). Meanwhile, the healthcare sector worldwide fuels growing use of antimicrobial textiles, a subset likely to benefit from the strong performance characteristics and reduced environmental footprint of MMFCs (Edgar and Zhang, 2020). Overall, these converging factors underscore the multifaceted and growing demand for MMCFs as the global textile industry seeks sustainable, high-performing materials.

Limitations to market growth

Despite growing interest in more sustainable fibres, several key obstacles stand in the way of widespread adoption of MMCFs. One challenge lies in securing regulatory approval for alternative solvents, which have the potential to make fibre production greener but are not yet authorized for large-scale use in many regions. Even when these solvents are allowed, most are still too expensive to compete with conventional options. Large, complex manufacturing operations also struggle to overhaul their supply chains, slowing shifts towards new production technologies (Orfanidou *et al.*, 2023). In terms of market dynamics, the volatility of textile demand can lead to an oversupply or a shortage of products, both of which reduce profitability along the supply chain (Doherty and Stalk, 2022; Arthur, 2024). Since textile markets are cyclical, the profitability of wood-based fibres also depends on broader competition with cotton and synthetics, as well as on paper pulp demand and production (Kallio, 2021).

Innovative wood-based fibres must enhance their appeal to designers and clothing labels who might be cautious of properties that differ from cotton or viscose, potentially hindering broad industry acceptance. While Lyocell might displace some viscose production capacity, it still faces production and technical performance challenges that prevent it from fully replacing viscose at this time. Consumers increasingly acknowledge the ecological impacts of textile production. However, many are reluctant to pay higher prices for apparel, limiting the market potential for MMCFs, which are still more expensive than conventional fibres (Orfanidou *et al.*, 2023). Successful adoption thus depends on collaborative efforts between fibre producers, apparel companies and regulators, all of whom must navigate environmental concerns, economic pressures and technological uncertainties.

Trade-offs with other forest products

The increasing demand for MMCFs affects other forest-based industries through both competitive and complementary pathways. On one hand, producing wood-based textile pulp can benefit solid wood product manufacturers such as sawnwood and plywood producers by creating additional demand for by-products like sawmill chips, which are feedstocks for pulp production. This synergy, however, weakens with strong growth in solid wood products, creating competition over feedstocks (Kallio, 2021). On the other hand, the same wood feedstocks are used to produce panels, paper pulp and paper, so additional MMCF output could reduce investment and capacity in those sectors. Model simulations indicate that for every tonne of increased textile pulp production, 0.5 to 0.6 tonnes of chemical paper pulp output are displaced, illustrating significant cross-industry trade-offs (Kallio, 2021). An advantage of MMCFs is that they can be produced from both coniferous and non-coniferous feedstocks, reducing competition for coniferous wood resources (Morland and Schier, 2020).

When evaluating market scenarios, GDP growth and evolving consumer preferences exert a stronger influence on MMCF production than direct competition over wood (Kallio, 2021; Morland and Schier, 2020). Much of the recent expansion in MMCF capacity arises from converting paper pulp mills, indicating the strong connection between the paper pulp and textile pulp sectors (Beck-O'Brien *et al.*, 2022). Further mill conversions will depend on the profitability of using wood for textiles relative to other sectors such as paper, packaging and bioenergy. In scenarios predicting slower economic expansion or reduced paper production, additional wood-based textile capacity may face few constraints, whereas high demand across multiple forest-product industries increases the chance of resource bottlenecks. This interconnected system warrants closer analysis to ensure that increased MMCF output aligns with sustainable land use and does not exacerbate competition for forest resources (Beck-O'Brien *et al.*, 2022; Kallio, 2021).

9.4.4 Energy and fuel

Bioenergy is a renewable form of energy derived from organic materials, collectively known as biomass. These materials can include forest residues such as woodchips and sawdust, agricultural by-products like crop waste, or dedicated energy crops grown specifically for fuel. Through various processes, such as combustion, fermentation, gasification, pelletization and anaerobic digestion, biomass can be converted into different forms of bioenergy. These pathways yield diverse products, including biodiesel, bioethanol, biogas, woodchips, pellets, bio-synthetic gas, and other advanced biofuels, all of which can be used to generate heat and electricity, power transportation, or form biomass-based materials (IEA, 2017). Woodfuel can be a primary product, sourced from forests specifically managed for fuel production, a product made from waste produced during manufacture of other products, or a competing product, where wood is allocated for fuel instead of being used for industrial products (Scarlat *et al.*, 2015).

Global energy demand has steadily increased since the industrial revolution, mainly driven by economic growth and technological progress. As the energy mix shifts in response to evolving technologies, the transportation sector, in particular, is expected to be a major source of demand growth – potentially rising by up to 25 percent by 2050 (IEA, 2024). While internal combustion engines may push oil use higher, advances in electric vehicles (EVs) introduce uncertainty around future fossil fuel consumption. Overall, rising living standards and development typically correlate with higher energy use, bringing challenges such as GHG emissions, higher energy prices, energy poverty, and potential social instability (Al Mubarak *et al.*, 2024). Ensuring reliable, affordable and sustainable energy supply is therefore critical, as it underpins continued economic development while mitigating the adverse effects of climate change and resource constraints.

Market trends

Modern bioenergy is the largest renewable energy contributor worldwide, representing 55 percent of renewables excluding traditional biomass use, and more than 6 percent of total energy supply (IEA, 2024). Between 2010 and 2023, modern bioenergy consumption rose by about 4 percent annually; however, to achieve net-zero targets, this growth rate must nearly double to 8 percent per year from 2023 to 2030. By 2030, biomass-based fuel deployment is set to expand by 4 EJ over 2023 levels, reaching 5.5 percent of global industry, building and transport energy consumption (IEA, 2024). Demand is expected to grow across all regions but is concentrated in Brazil, China, Europe, India and the United States, which together account for more than two-thirds of this growth. Each of these regions applies a suite of policies such as mandates, GHG performance criteria, and direct investment incentives, to support the expansion of liquid, gaseous and solid biofuels (IEA, 2024).

India is boosting its use of liquid biofuels, biogases, solid biomass and hydrogen by nearly 40 percent until 2030 through production incentives and blending targets (IEA, 2024). Brazil, responsible for 12 percent of the overall increase, is raising liquid biofuel blending requirements and has announced a USD 3.2 billion green hydrogen incentive program (IEA, 2024). Meanwhile, China's renewable fuel use, spanning biogas, solid biomass, biodiesel blending and hydrogen, continues to rise in industry, building and transport (IEA, 2024). Overall, bioenergy is anticipated to provide about 100 EJ of global primary energy by 2050, with around 60 percent in the form of solid bioenergy, 30 percent as liquid fuels and 10 percent as biogas (IEA Bioenergy, 2023). Nonetheless, regional contexts vary significantly. For example, in many high-income countries, wood-based solid bioenergy is promoted as an alternative to fossil fuels, while in lower-income regions, traditional woodfuel remains a primary cooking and heating resource with associated health and environmental challenges. Consequently, how woodfuel use and modern bioenergy policy evolve will be pivotal in shaping a sustainable future energy landscape.

Traditional woodfuel

Woodfuel continues to be one of the most widely used sources of energy for domestic heating and cooking. Although the proportion of wood used for industrial roundwood, sawlogs and pulp has increased since 1961, the total volume of wood used as fuel has remained fairly consistent in the last 60 years, declining from 60 percent in 1961 to 49 percent in 2022 (FAOSTAT, 2024). In 2023, the trend continued with close to 50 percent of harvested wood being used as fuel or in the production of charcoal and pellets (FAOSTAT, 2024). In Asia, this figure was 60 percent, while in Africa 90 percent of wood was used as fuel (FAOSTAT, 2024; FAO, 2024). However, new estimation procedures suggest that the use of woodfuel in these regions could be even higher (Steel *et al.*, 2025). Accurate figures of woodfuel usage are difficult to estimate owing to the frequently unregulated nature of its collection and use, however this practice has drawn international attention for several reasons. Woodfuel collection and use is linked with forest degradation in some parts of the world. Direct combustion of wood is also an inefficient practice, both in terms of energy generated as well as in terms of the lost opportunity for value creation. Finally, the burning of woodfuel has prompted concerns about short-term GHG emissions as well as indoor air quality, increasing the risk of respiratory illnesses (Bailis *et al*., 2015). The continued use of woodfuel as a primary source of energy is a significant factor in the long-term success of a forest-based bioeconomy.

In 2023, "modern solid bioenergy", which includes various kinds of biomass-derived solid fuels except the traditional combustion of woodfuels, accounted for 16 EJ, or 3.5 percent of final energy use globally, while traditional bioenergy accounted for an additional 19 EJ (IEA, 2024). Modern solid bioenergy is expected to rise to 18 EJ by 2030, largely driven by industrial processes such as expanding sugar and ethanol production in India, substitution of traditional biomass in sub-Saharan Africa, and the increasing use of modern biomass stoves and boilers in Europe. However, the overall impact of these shifts is a 5 percent decline in total global solid bioenergy consumption in 2030 (IEA, 2024). Improvements in terms of shifting away from traditional woodfuel use will depend on several interrelated factors such as urbanization, access to modern energy sources, supportive policies for cleaner cooking, and resource availability. As populations move from rural to urban areas, energy demand typically rises, but the outcome for traditional woodfuel varies depending on affordability and reliability of alternatives such as electricity or non-woodfuels. In many developing regions, governments are promoting transitions from traditional biomass use to modern combustion via cleaner cookstoves and more efficient charcoal production technologies (FAO, 2022). In India, biomass use remains relatively steady yet involves a shift from locally gathered traditional fuels towards modern bioenergy such as wood pellets and liquid biofuels, underscoring that the pattern of future woodfuel use will differ widely depending on local socioeconomic conditions, energy policies and resource constraints (IEA, 2024).

Wood pellets

The residues generated from timber harvesting and industrial wood manufacturing are often processed into solid fuel products like wood pellets, which have improved energy values and can be more conveniently transported. Over the past decade, the pellet market has grown substantially, partly due to the advantages of pelletization in overcoming biomass limitations related to high moisture content, low energy density and decay (Saletnik *et al.*, 2022). Global wood pellet production surged from 1.7 million tonnes in 2000 to 55.7 million in 2018 and continued to rise at about 5 percent annually from 2019 to 2020 (Rodriguez, 2022; Saletnik *et al.*, 2022). In 2023, global wood pellet production was 47 million tonnes, with 20 million tonnes being produced in EU-27 countries, 13 million tonnes from the United States and Canada, and 8 million tonnes from Asia, where Viet Nam-led production and Japan and the Republic of Korea emerged as significant importers (FAOSTAT, 2024). The European market accounted for 44 percent of global production and 50 percent of consumption. Within the European Union (EU-27), Austria, Germany, Latvia and Sweden lead wood pellet production as a result of supportive policies such as tax exemptions, subsidies and sustainability requirements. This regulatory environment has contributed to the rapid expansion of pellet use across Europe, in power plants as well as for thermal energy in individual households and industrial settings.

After two decades of continuous expansion and record sales for pellet-based appliances, global pellet production stalled in 2023 as supply shortages were driven by the 2022 EU embargo on Belarusian and Russian Federation forestry products, consumer stockpiling during the European energy crisis, and policy shifts in key markets such as France and Italy. Supply was compensated by production increases in France, Germany, Poland and Spain, as well as additional imports from Brazil, the United States and Viet Nam. Looking ahead, the outlook for wood pellets remains uncertain as high production costs from elevated electricity prices, evolving subsidy frameworks, and shifting consumer preferences continue to shape market dynamics (IEA, 2024).

Biofuels

Agricultural crops and residues are one of the primary feedstocks for biofuels, most notably sugarcane, corn (*Zea mays*), soybeans, and African oil palm (*Elaeis guineensis*). Biofuel production is often associated with several positive socioeconomic impacts such as job creation and energy security. However, expanded biofuel production often results in conversion of land towards agricultural use while diverting the production of food crops needed to maintain food security (Antar *et al*., 2021). Biofuel production also generates large volumes of waste as often edible parts of a plant are processed, and can involve inefficient conversion systems depending on the technology used (Antar *et al*., 2021). A solution to the challenges posed by agricultural feedstocks for bioenergy is to meet that demand with forest-derived biomass, including plant matter removed from forests and waste from processes such as harvesting and sawmilling.

Biofuel use in road transport is expanding globally, with Brazil, Europe, India, Indonesia and the United States accounting for 85 percent of growth (IEA, 2024). These countries and regions have strengthened mandates, GHG intensity targets and financial incentives in support of the sector. Specifically, Brazil, India and Indonesia are likely to drive demand increases of around 27 billion litres of biofuels, bringing total global road biofuel demand to 205 billion litres by 2030 (IEA, 2024). This increase in Asia and South America is supported by economic growth and relatively slow EV adoption. However, overall transport fuel demand is projected to peak in 2028 and decline thereafter, significantly reducing demand for road biofuels in 2030. This shift is driven by a combination of EV adoption and vehicle efficiency improvements. Renewable diesel will likely continue to gain significance, particularly in Europe and North America, due to its low GHG intensity and ability to blend with conventional fuels at high concentrations, supporting policy goals towards reduced emissions from the transport sector (IEA, 2024).

Sustainable aviation fuels

Aviation accounts for approximately 2.8 percent of global carbon emissions and is growing rapidly, with air passenger numbers projected to rise at an annual rate of 3.3 percent between 2019 and 2040, reaching 7.8 billion travelers. To meet net-zero targets by 2050, airlines plan to increasingly shift their fuel from fossil-based to sustainable aviation fuels (SAFs; IATA, 2025). Three technology pathways are certified for SAF production: (1) Fischer-Tropsch, (2) alcohol-to-jet, and (3) hydroprocessed esters and fatty acids, drawing on a variety of feedstocks that include, among other sources, forestry residues (Vardon *et al.*, 2022). Lignocellulosic biomass and waste are considered the most environmentally friendly since they do not compete for land with food/feed crops (Ng *et al.*, 2021). SAFs made from wood-based feedstocks lead to GHG emissions savings of around 80 percent when compared with fossil-based jet fuel: using wood logging residues in the US Pacific Northwest reduces the global warming potential by 78 percent (Ganguly *et al.*, 2018), converting softwood residues into SAF in the EU-28 reduces GHG emissions by 80 percent (Puschnigg *et al.*, 2023), and using wood logging residues in Sweden leads to GHG emissions savings of 90 percent for a variety of woodfuel-based production chains (Björnsson and Ericsson, 2024).

SAFs currently account for less than 0.5 percent of global jet fuel demand due to high production costs, feedstock limitations and insufficient policy incentives in the aviation sector relative to road transport (Björnsson and Ericsson, 2024). Overcoming these barriers will require clear policy frameworks, greater industry awareness and further technological advancements, such as economies of scale at biorefineries, to drive down production costs. A wide range of legislation and policy relevant to SAF exists (Ng *et al.*, 2021). In the United States and Europe, new growth in the biofuels sector in 2030 is largely within aviation and maritime biofuels, propelled by mandates and incentives (IEA, 2024). The European Commission's RefuelEU Aviation mandate exemplifies one such policy intervention. It stipulates increasing blend targets for advanced and synthetic fuels, rising to 5 percent in 2030, 32 percent in 2040 and 63 percent by 2050 (Puschnigg *et al.*, 2023). By excluding less sustainable feedstocks and prioritizing lignocellulosic and synthetic alternatives, these measures could accelerate the aviation sector's decarbonization while accommodating the projected growth in air travel demand.

Limitations to market growth

The overall impacts of bioenergy production and use vary with feedstock type, management practices, regional climate, scale of deployment, and existing land-use or energy systems. Forestry residues are widely viewed as a more sustainable option since forest lands are less likely to compete with agricultural land designated for food production (Calvin *et al.*, 2021). Wood and forest waste, for instance, are major feedstocks in the biomass energy sector, but if they are not carefully managed their use can result in deforestation, soil erosion and ecosystem damage. Competition for these feedstocks is already intense, and increased demand for SAFs could further strain resources and drive increased costs across all dependent sectors. The combustion of biomass releases GHGs and particulate matter, including carcinogenic elements and toxic metals. These emissions pose risks when generated by multiple small-scale users, such as wood-burning stove owners, which do not operate under centralized emission controls (Al Mubarak *et al.*, 2024). According to the International Energy Agency (IEA), net GHG reductions from bioenergy occur when: (1) biomass is grown sustainably or sourced from residues and waste, (2) it is converted efficiently, and (3) it displaces more GHG-intensive fuels (D'Adamo *et al.*, 2021). Sustained bioenergy expansion depends on balancing cost-effective feedstock sourcing, mitigating upward price pressures on food crops, and addressing efficiency and land use trade-offs (Al Mubarak *et al.*, 2024).

Although biomass can be transported globally and therefore is not strictly bound by location, its market growth is limited by economic constraints, chiefly the cost of feedstock supply and transportation. Feedstock prices can constitute up to 80 percent of the operating costs for biomass plants and substantially influence the cost of electricity generated (Al Mubarak *et al.*, 2024). Bioethanol production costs in Brazil and India are able to come close to the cost of traditional liquid fuels, however in most other parts of the world, biofuels are more expensive than traditional fuels (IEA, 2024).

9.4.5 Biochemicals and bioplastics

Biochemicals and bioplastics are emerging as key components of the forest-based bioeconomy, offering sustainable alternatives to fossil-derived chemicals and plastics. These materials are produced using wood pulp and its by-products as feedstocks, employing a diverse range of production technologies (Hurmekoski *et al.*, 2018). Biomass components such as cellulose, hemicellulose, lignin and extractives are extracted through thermochemical, chemical and biological processes, then refined into platform chemicals or intermediates. These intermediates serve as precursors for high-value and specialized products, including adhesives, coatings, solvents and pharmaceuticals (Haile *et al.*, 2021). Among biochemicals, drop-in chemicals like ethylene and propylene share an identical molecular structure with their fossil-based counterparts, allowing for seamless integration into existing chemical manufacturing processes. Smart drop-in chemicals, such as 1,4-butanediol and succinic acid, offer production pathways with advantages like improved energy efficiency and lower toxicity compared with conventional chemicals. Meanwhile, dedicated biochemicals such as lactic acid possess unique molecular structures and properties, enabling their use in innovative products beyond fossil-based alternatives (Hurmekoski *et al.*, 2018).

Although a number of chemicals and polymers can be produced within this sector, only certain product pathways have been identified as having competitive quality, biomass utilization efficiency and financial viability. Lignin, for example, is typically used to produce bioethanol, or energy and heat on site, however it is also promising as a feedstock for high-value end products such as vanillin, phenol derivatives and carbon fibres. Commercializing this pathway would require improvements in pre-treatment technology to generate higher quality lignin residues, which many biorefinery operators struggle to achieve (Martins *et al.*, 2022; Rajan *et al.*, 2024). This sector presents an interesting contrast, where feedstocks could be abundantly sourced from pulp mills and biorefineries, yet industrial-scale production faces technical and financial challenges affecting the competitiveness of biochemicals in the market (Hurmekoski *et al.*, 2022a; Rajan *et al.*, 2024).

Bioplastics are polymer materials derived from wood-based sugars and lignin, and are increasingly being used as replacements for petroleum-based plastics in packaging, consumer goods and industrial applications. Pre-processing (i.e. pulping and fractionation) of wood biomass enables the extraction of lignin for bioplastics. Advances in biorefinery technologies allow for the integrated production of these materials alongside traditional forest products, enhancing their economic and environmental sustainability (Martins *et al.*, 2022). However, the environmental advantages of these novel products should not be overstated.

Despite presenting climate benefits from lower intensity manufacturing processes and reduced reliance on petroleum, bioplastics are not necessarily biodegradable, or are biodegradable only under special conditions that cannot be easily replicated in normal industrial composting and recycling centres (Ögmundarson *et al.*, 2020).

When integrated with pulp mills or biorefineries that produce a range of products, biochemical and bioplastic production can be energy and cost efficient. However, their overall environmental performance depends on their production technology and end-of-life management (IEA Bioenergy, 2020). A review of life cycle assessment (LCA) studies reported varying levels of CO_2 emissions from the production of biobased chemicals compared with their fossil-based counterparts. The source of raw materials and end-of-life treatment significantly influences these results. When related to adverse land-use change or unsustainable harvesting, biochemicals can show higher environmental impacts than conventional chemicals. Composting or energy recovery can maintain lower emissions, whereas landfilling without energy recovery may negate or even exceed the climate benefits achieved during production (Ögmundarson *et al.*, 2020). Biochemicals and bioplastics are broadly found to have better environmental performance than fossil-based products, however several sustainability-related externalities such as their contribution to ecotoxicity and acidification have not yet been conclusively determined (IEA Bioenergy, 2020).

Market trends

The global biobased chemicals market was valued at USD 110 billion in 2025 and is projected to grow at a compounded annual growth rate of 9.6 percent between 2026 and 2034 (Fortune Business Insights, 2026). Within the European bioeconomy, biobased chemicals and plastics remain a relatively small sector, accounting for 7 percent of total annual turnover in 2021. Production is concentrated in key pulp-producing regions, such as Brazil, Canada, China, Europe and the United States, highlighting the strong link between pulp mills and biorefining. Future projections for the production of biobased bulk chemicals vary significantly depending on market conditions. Under optimistic scenarios, the production of bulk chemicals from renewable resources is projected to reach 113 million tonnes by 2050 (representing a 38 percent market share), while more conservative estimates suggest an increase to 26 million tonnes (a 17.5 percent share) (IEA Bioenergy, 2020). Given the sector's vast product diversity, estimating its overall market share remains complex. Some biochemicals, such as lactic acid and mono-ethylene glycol, have reached mature production stages, whereas others, including succinic acid and 2,5-furandicarboxylic acid, are still in their early phases of commercial development (IEA Bioenergy, 2020).

In 2023, bioplastics accounted for 0.7 percent of global plastic production and 1.4 percent of total plastics produced in Europe (defined here as EU-27, Norway, Switzerland, and the United Kingdom). Global production has grown modestly but steadily, increasing from 1.2 million tonnes in 2018 to 3 million tonnes in 2023. It is projected to reach 5.73 million tonnes by 2029 (Plastics Europe, 2024; European BioPlastics, 2024). Of the 3 million tonnes of bioplastics produced in 2023, 10 percent originated in North America, 25.2 percent in Europe, 34.5 percent in China and 21.6 percent in the rest of Asia (excluding Oceania and Türkiye). European production has expanded from 0.2 million tonnes in 2018 to 0.8 million tonnes in 2023, with France, Germany and Italy emerging as the leading producers (Plastics Europe, 2024). Approximately 45 percent of bioplastics are used in packaging, while other key applications include the automotive and transport sector, novel textiles and fibres, and consumer goods (European BioPlastics, 2024). Although bioethanol plays a major role in this sector, it is covered in the energy and fuel section of this report. However, bioethylene – a co-product of bioethanol – along with polylactic acid and polyhydroxyalkanoates, are considered among the most promising emerging biopolymers (IEA Bioenergy, 2020).

Drivers of demand

Globally, the biobased chemical industry is anticipated to experience moderate yet sustained growth until 2050, driven primarily by rising consumer demand, policy shifts towards more sustainable production pathways, and technological innovations in converting biomass into higher-value chemicals. In Europe, much of the impetus for biobased chemical development comes from the region's policy focus on the bioeconomy and the high maturity level of its existing industrial infrastructure. For example, The EU policy initiative RoadToBio (2017–2019) outlined a roadmap to increase the share of biobased feedstocks in the European organic chemical industry from 10 percent in 2015 to 25 percent in 2030 (Panchaksharam *et al.*, 2019). In emerging economies, demand will likely be driven by the need to integrate biorefinery processes within existing pulp mills with the goal of benefiting from the increased opportunity for profit and environmental sustainability. Biodegradable fertilizers and other agricultural aids are also driving demand for biochemicals due to their improved environmental performance in the context of the urgent need to increase agricultural productivity worldwide (Panchaksharam *et al.*, 2019).

Advancements in biorefinery technologies are one of the key drivers of bioplastic expansion, with integrated biorefineries enabling cost-competitive production, improved yields, and better efficiency and material performance (Pandey and Sharma, 2024; Jayakumar *et al.*, 2023). Governments worldwide are implementing restrictions on conventional plastics, encouraging the use of biobased and biodegradable alternatives. The EU Single-Use Plastics Directive, adopted in 2019, and China's multiple plastic waste regulations are examples of policies accelerating bioplastic adoption. These policy interventions, which promote recycling, composting and extended producer responsibility, are enhancing the market viability of biodegradable and compostable bioplastics (Jayakumar *et al.*, 2023). Major brands and retailers are increasingly incorporating biobased materials in their supply chains. Companies such as Unilever, Coca-Cola and IKEA have made commitments to replace fossil-based plastics with renewable alternatives, indicating the commercial-scale adoption of certain products. These industry-related interventions to meet sustainability targets are complemented by increased consumer awareness of plastic pollution and climate change, driving bottom-up demand for innovative bioplastics, especially in the packaging sector (Gaffey *et al.*, 2021; Hurmekoski *et al.*, 2018).

Limitations to market growth

The biochemical and bioplastics sectors face several hurdles that collectively limit their growth potential. Feedstock availability remains a central challenge, as biomass supply is affected by fluctuations in agricultural and forest yields, regional land-use policies and competition with other biomass-consuming industries. This "competition triangle" places nascent biochemical and bioplastics producers in direct competition with both bioenergy and petrochemical manufacturing pathways (Panchaksharam *et al.*, 2019; Rajan *et al.*, 2024). Meanwhile, scaling up innovative conversion technologies requires significant capital expenditure and developing and introducing new products at industrial production scale into markets requires long timelines (Hurmekoski *et al.*, 2018; IEA Bioenergy, 2020). The industry's reliance on specialized pre-treatment for efficient biomass utilization further increases investment costs, making modern biorefineries difficult to set up in small or risk-averse markets. Furthermore, conflicting sustainability benefits related to recyclability, compostability and carbon substitution benefits complicate the widespread adoption of biobased alternatives as alternatives to fossil-fuel products (Ögmundarson *et al.*, 2020).

On the policy side, an inconsistent regulatory environment amplifies uncertainty in market development and capital allocation. The absence of global standards for biodegradability and compostability creates inconsistencies in how bioplastics are classified, marketed and disposed of (Rajan *et al.*, 2024). While some regions have implemented supportive legislation and robust infrastructure for biobased products, others lag in addressing regulatory gaps or establishing incentives for reducing carbon footprints in chemical manufacturing (Panchaksharam *et al.*, 2019). This disparity restricts investment in research and development, undermining the potential of emerging technologies, such as AI-driven process optimization, to lower costs, enhance feedstock flexibility and improve supply chain resilience. Even when supportive policies are in place, the biochemical sector must navigate demanding approval processes and comply with strict environmental regulations. In this context, bridging technical and cost barriers, optimizing co-product recovery in facilities like pulp mills, and ensuring robust end-of-life solutions are all vital steps increasing production of biobased chemicals and plastics (Rajan *et al.*, 2024).

Trade-offs with other forest products

The expanding biochemical and bioplastics market presents significant potential trade-offs with existing forest-based industries, particularly pulp and paper, wood-based textiles and biomass for energy. To ensure a sustainable feedstock supply, modern biorefineries will need to integrate a diverse range of inputs beyond wood, including recycled fibres and non-woody biomass. Meanwhile, advanced data analytics and machine learning could drive intelligent automation, optimizing production processes for efficiency and resource use (Rajan *et al.*, 2024). Given their strong ties to pulp and paper mills, the ongoing shift towards specialty and niche paper products will likely influence the cost, efficiency and production timelines for chemicals and polymers. Additionally, pulp mills operate under strict environmental regulations due to sustainability concerns, and integrating advanced chemical processes may necessitate further compliance with waste management protocols and water usage limits, increasing downstream production costs. A rapid expansion of bioplastics production could drive higher cellulose demand, potentially raising the costs of inputs and intermediates for wood panel industries, and paper and textile manufacturers. Moreover, lignin, a key feedstock for bioplastics, biochemicals and bioethanol, plays a crucial role in this sector. As bioethanol remains a mature and expanding product, increased demand for lignin in material applications could create trade-offs between material and energy uses (Rajan *et al.*, 2024).

Modern biorefineries based on lignocellulosic or timber-based feedstocks will need to produce a spectrum of niche products to improve their competitiveness against conventional and agriculture-based production processes. Although biochemicals and bioplastics hold a weak share of global markets, a small increase in demand for these products could strongly benefit the profitability of biorefineries (Hurmekoski *et al.*, 2018). The biochemicals and bioplastics sector offers an opportunity to further diversify the forest-based bioeconomy and improve downstream profitability, however its successful integration will depend on several factors. Achieving a balanced approach that leverages new wood-based by-products without wholly displacing existing processes, optimization of resource flows via advanced biorefinery management, and ensured adherence to sustainability regulations are some key elements of this transition (Hurmekoski *et al.*, 2022a). This balance is critical for realizing a bioeconomy that supports multiple forest-derived industries without impacting the ecosystem services that forests provide.

9.4.6 References

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9.5 Regional forest trends and wood supply

9.5.1 Regional[17] overview of forests and wood supply

Europe and North America

Europe and North America together account for a significant proportion of the world's forest resources, with about 1.04 billion ha of forest in Europe and about 744 million ha in North America (FAO, 2025). Both regions are characterized by high levels of forest management, well-developed forest industries and relatively stable forest areas. Notably, North America is home to extensive primary forests, particularly in Canada. Together with Europe, these regions account for half of the world's primary forest area (FAO, 2025).

Europe has one of the highest proportions of forests under formal management plans, covering about 96 percent of its total forest area. More than half (53 percent) of Europe's forests – about 515 million ha – are managed primarily for production, a figure that falls to about 29 percent if the Russian Federation is excluded (Egenolf *et al.*, 2022). In North and Central America, 222 million ha (29 percent) of forest land is used primarily for production (FAO, 2025). Europe's commitment to sustainable forest management is reflected in stable or slightly declining proportions of production forests over the last three decades (54 percent in 1990 to 53 percent in 2025), as well as extensive certification schemes and detailed forest regulations.

In terms of planted forests, Europe has about 80 million ha – among the largest in the world – providing wood for sawnwood, pulp, and a growing bioenergy sector. Planted forests in North America total about 48.3 million ha and play a key role in supplying raw materials for lumber, pulp and paper (FAO, 2025).

Asia and Oceania

Asia and Oceania have the largest area of planted forests in the world, at 151 million ha, representing 19 percent of its total forest area, with East Asia alone accounting for 106.6 million ha. Plantation forests account for 71 percent of the total planted forest area in Asia. While Oceania's planted forest area is relatively modest at 4.9 million ha (representing only 3 percent of its total forest area), its proportion of plantation forests is among the highest in the world at 92 percent (FAO, 2025).

Planted forests and trees outside forests are becoming increasingly important in meeting the Asia-Pacific region's growing demand for wood (FAO, 2019). The expansion of planted forests in Asia is increasingly driven by smallholder forestry, particularly in areas where large-scale conventional plantations are constrained by high population densities and competing land uses.

Most planted forests in Asia are monocultures, which raises concerns about their ability to provide a wide range of ecosystem services, especially when compared with more heterogeneous forest types. Moreover, maintaining or even increasing production from these planted forests will require addressing several interrelated constraints: the limited availability of productive land (especially in the presence of high population densities and competing land uses), and the impacts of climate change on forest growth and health. The conversion of natural forests to oil palm plantations remains a major concern, particularly in Southeast Asia. This trend not only contributes significantly to deforestation and biodiversity loss but also raises questions about the long-term resilience of ecosystems (FAO, 2019).

[17] Regional summaries of Global Forest Resource Assessment (FRA) data refer to the regions used in that reporting process and can be identified here: https://fra-data.fao.org/assessments/fra/2025. The major difference with FOROM modelling regions (Table A2 and Table A3) is the inclusion of The Russian Federation in Asia in FOROM versus in Europe (FRA).

Africa

Africa's forests cover almost 16 percent of the world's forest area (FAO, 2025). The area of managed forest in Africa is relatively low compared with other regions, with less than 25 percent of forests under formal management plans. The area of planted forests is estimated at 14.1 million ha – representing only 2 percent of the continent's total forest area – while plantation forests cover about 11.8 million ha, representing 83 percent of the total area of planted forests (FAO, 2025).

Africa's industrial demand for roundwood is about 100 million m^3 per year, of which 36 million m^3 comes from natural forests and about 30 million m^3 is imported. Plantations supply the rest (FAO and Dalberg Catalyst, 2024).

Latin America and the Caribbean

The Latin America and the Caribbean (LAC) region accounts for about 20 percent of the world's forests (FAO, 2025). These forests include half of the world's tropical forests and a quarter of its mangroves (Blackman, 2020). South America has 299 million ha of primary forest – about 49 percent of its total forest area – while Central America has 1.2 million ha, or about 91 percent of its forest area (FAO, 2025).

Forests designated primarily for production in South America cover 122 million ha – 15 percent of the continent's total forest area – while Central America and the Caribbean have 1.9 million ha under management (4 and 22 percent of their forest area, respectively). The total area of planted forests in South America is estimated at 17.3 million ha. In South America, plantation forests account for nearly all planted forest area, underlining the region's heavy reliance on plantations for timber and other forest products (FAO, 2025).

Plantation forests in LAC have expanded by about 14 million ha between 1990 and 2020 (ECLAC, 2021). Brazil, Chile and Uruguay have led this expansion, planting fast-growing species such as eucalyptus and pine on previously cleared or degraded land. These plantations provide raw material for the pulp and paper industry and help to reduce deforestation pressure on native forests (Nambiar, 2021).

9.5.2 Smallholder forestry systems

Smallholders play an increasingly important role in meeting Asia's growing demand for timber, particularly for pulpwood and other commercial products (Midgley *et al.*, 2017). This type of forestry is particularly prevalent in countries such as India, Indonesia, Thailand, Viet Nam, and parts of China. In India, for example, smallholders provide about 80 percent of the roundwood feedstock, making farm-grown timber an essential part of the country's wood supply (Lal, 2015).

In Africa, smallholder agroforestry plays an important role in addressing the region's supply–demand challenges of forest products, driven by several factors. In East Africa, the prospects for large-scale expansion of timber production through commercial private sector participation are limited due to the shortage of continuous blocks of land available for plantation (Ayana, 2021). Regulatory interventions such as the ban on harvesting wood products from state forest reserves, such as those in Kenya, further limit regional timber supplies (Ayana, 2021). These conditions have historically encouraged smallholder farmers in the region to adopt agroforestry practices, which have enabled them to grow and sell timber on the market for fuel and construction purposes (Holding-Anyonge and Roshetko, 2003; Chamshama *et al.*, 2009). At the same time, trees grown for timber production have the added benefit of improving crop yields, for example by providing shade for coffee plants (Mengitsu, 2023).

Smallholder forestry also contributes significantly to planted forest area in South America. For example, in Brazil, out-grower schemes using eucalyptus hybrids provide economic benefits to rural communities, restore degraded soils, and reduce pressure on native forests (de Moraes Gonçalves *et al.*, 2020).

9.5.3 Forest management regimes

Forest management regimes strongly influence the volume, quality and sustainability of wood supply in both the short and long term. The commercial production of timber from naturally regenerated or planted forests may be subject to even-aged or uneven-aged management. In boreal and temperate regions, even-aged management has traditionally involved clear-cutting; however, many countries now use retention approaches to conserve biodiversity and maintain structural diversity (Chaudhary *et al.*, 2016). These methods often rely on long rotations with silvicultural thinning, which produce high-value sawlogs as well as a substantial volume of pulpwood from thinning.

Uneven-aged forest management and continuous cover forestry (CCF), in particular, are gaining traction in the framework of the European Union (EU-27)'s new forest strategy for 2030 (European Commission, 2021), with the goal to create multi-layered stands that increase structural complexity. Depending on the forest type, maintaining a permanent forest canopy can play a critical role in protecting biodiversity, maintaining soil quality and regulating water cycles.

Moreover, the balance between timber production, carbon sequestration and recreational value is intended to ensure that forest management is both economically and environmentally sustainable. This is closely aligned with the principles of sustainable forest management (European Commission, 2021; Mason *et al.*, 2021). These systems now cover 22 to 30 percent of European forests with higher adoption in central and southeastern Europe. However, simulations of transitioning forest practice to CCF show that converting even-aged stands to CCF, particularly when starting with mature stands, can maintain economic viability, although with an expected short-term reduction in timber volume of around 30 percent compared with traditional even-aged systems. (Hessenmöller *et al.*, 2018; Mason *et al.*, 2021).

In tropical regions, short-rotation forestry typically focuses on rapidly growing species with separate production of sawlogs and pulpwood. Among conifers, pinus is the most widely used genus, accounting for 60 percent of all conifers. Among hardwoods, eucalyptus and acacia (*Acacia* spp.) are the most commonly planted genera, together accounting for half of all hardwoods, although eucalyptus is mainly used for pulp production (Ramage *et al.*, 2017). Although short rotations can meet the rising demand for wood fibre, particularly non-coniferous pulpwood, this approach sometimes raises concerns about long-term ecological sustainability (Lauri *et al.*, 2021).

When degraded Brazilian pastures are replaced by short-rotation eucalyptus and pinus, soils maintain carbon at levels similar to pasture for up to 34 years after conversion, while sustaining high stemwood productivity (Cook *et al.*, 2014). Similarly, hydrological outcomes depend on management and site conditions: a Brazil-focused review finds eucalyptus water use is comparable to native forests and crops, and that agroclimatic zoning, appropriate species selection, lower planting densities and shorter rotations can avoid negative water impacts (Medeiros *et al.*, 2025).

9.5.4 References

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