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FOREST PRODUCTS IN THE GLOBAL BIOECONOMY

Enabling substitution by wood-based products and contributing to the Sustainable Development Goals

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Acronyms

CLT	cross-laminated timber
CRGE	climate-resilient green economy
GDP	gross domestic product
GFG	Global Forest Goals
GHG	greenhouse gases
GSGDA	Ghana Shared Growth and Development Agenda
IPCC	Intergovernmental Panel on Climate Change
IRP	International Resource Panel
LCA	Life Cycle Assessment
LVL	laminated veneer lumber
MF	material footprint
MMCFs	man-made cellulose fibre
NWFPs	non-wood forest products
SDGs	Sustainable Development Goals
SSP	shared socioeconomic pathways

List of tree species

Common name	Scientific name
Douglas fir	*Pseudotsuga menziesii* (Mirbel) Franco
Eucalypt	*Eucalyptus* sp.
Fir	*Abies* sp.
Larch	*Larix* sp.
Loblolly pine	*Pinus taeda* L.
Longleaf pine	*Pinus palustris* Mill.
Moringa	*Moringa stenopetala* (Baker f.) Cufod.
Pine	*Pinus* sp.
Red maple	*Acer rubrum* L.
Shortleaf pine	*Pinus echinata* Mill.
Slash pine	*Pinus elliottii* Engelm.
Spruce	*Picea* sp.
Sugi	*Cryptomeria japonica* (L.f.) D.Don
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western red cedar	*Thuja plicata* Donn ex D.Don
Yellow poplar	*Liriodendron tulipifera* L.

Foreword

FAO has adopted a new Strategic Framework to guide its work from 2022 to 2031. It seeks to support the Agenda 2030 through the transformation to more efficient, inclusive, resilient and sustainable agri-food systems that leave no-one behind. The Organization recognizes the key role of a bioeconomy that balances economic value and social welfare with environmental sustainability in achieving the Agenda 2030 goals.

FAO has assumed a lead role in shaping the global debate around the bioeconomy and its contribution to enhancing food security and nutrition worldwide. Increasing the sustainable use of bio-based products to replace fossil-fuel based products will be essential if the world is to meet many of the SDGs, including, but not limited to, SDG 12 (Responsible consumption and production), SDG 13 (Climate Action) and SDG 15 (Life on land).

This comprehensive report brings together the most up-to-date knowledge on the role of forest products in the global bioeconomy. It offers policy makers, the private sector and researchers a wide range of practical actions to increase the contribution of forest products to climate change mitigation and to sustainable development.

Mette Løyche Wilkie
Director
Forestry Division
FAO

As recognized in the ACSFI Strategic Framework 2020 – 2030, an initiative that focuses on the bioeconomy and substitution of fossil fuel based and greenhouse gas-intensive products with renewable forest based products, is essential for the ACSFI to realize its medium-term outcome of strategic actions stimulated, and partnerships facilitated, to promote a circular forest-based bioeconomy and healthy and productive ecosystems.

This comprehensive report is an essential guide for the ACSFI and its stakeholders to understand how to best increase the contribution of forest products to sustainable development.

It demonstrates the wide range of innovative forest-based products available for sustainable solutions to reduce our dependency on non-renewables and provides a clear set of recommendations for the private sector, governments and international cooperation bodies to both enable and boost forest product substitution.

Carina Hakansson
ACSFI Chair
2019 - 2021

Ross Hampton
ACSFI Chair
2021

Executive summary

There is a growing understanding that a rethink of the global economic system is necessary to address the root causes of the unsustainable use of natural resources and achieve sustainable development. The bioeconomy has emerged as a concept for tackling challenges such as the overconsumption of and overreliance on non-renewable natural resources. The bioeconomy commonly refers to the use of biological resources and processes. Bio-based materials can substitute fossil sources to produce energy, food, feed, fibre, and other manufactured goods. The development of the sustainable bioeconomy is considered as a way of helping to reach the Sustainable Development Goals. This report addresses the role of forest products in the global bioeconomy. In particular it explores how substitution of greenhouse gas intensive products by wood-based products could help replace fossil-based and GHG-intensive products. It explores how substitution by forest products could support sustainable development.

The bioeconomy can be defined in many ways and hence there are many different interpretations of the concept. Several countries around the world have a dedicated bioeconomy strategy or action plan. Other countries do not have a dedicated strategy but may have strategies or action plans that relate to the bioeconomy. The focus of these strategies and action plans varies significantly; many of them relate to innovation and biotechnology to develop new value-added products (e.g. chemicals, packaging or biofuels) or improve the productivity of biological resources, and bioenergy. A smaller number address issues related to rural development, biodiversity and sustainable management, and biomass supply. The role of ecosystem services and sustainability is acknowledged in several strategies, but not always elaborated in detail. What is more, the role of forests and the forest sector is not always clearly acknowledged in bioeconomy strategies or the related strategies and action plans.

Forests and the forest sector are nevertheless important components of a sustainable circular bioeconomy. The sector has long manufactured numerous everyday products. For some of these products, significant changes have occurred recently. Graphic paper is one product group marked by structural change, where demand has stabilized or has even declined in some world regions over the last 15 years, due to the adoption of internet and electronic media. Some studies estimate that a decrease in global newsprint, printing and writing paper consumption could by 2030 make available an additional 229 – 259 million cubic metres of roundwood equivalent for other uses. New products and technologies are emerging, aiming to increase the added value of wood products, decrease the carbon and water footprint of products and processes, reduce pollution and waste generation, and improve circularity. Engineered wood products and wood-based textile fibres are two such emerging forest product categories. The production and consumption of engineered wood products are rising, mainly due to increased application in wood-frame multistorey construction, facilitated by building codes that are based on better, up-to-date knowledge of wood as a construction material and the possibility of prefabricated elements and modules that can readily be used in the construction process. Cross-Laminated Timber (CLT) is considered for many construction applications (including floors, walls, and roofs) to substitute non-renewable, GHG-intensive construction materials, and for its good acoustics and insulation performance, among other characteristics. While comprehensive statistics are not yet available for production, trade and apparent consumption of engineered construction materials, studies exist that estimated CLT production will be three million cubic metres by 2030. Meanwhile, wood-based textile fibres have seen their global consumption increase since the last decade, and it could take an even larger share of the market, which is currently dominated by petroleum-based fibres. Lyocell fibres, for example, can be used for textiles, nonwovens, and specialty papers. Lyocell has properties that are similar to viscose and polyester yet is more environmentally friendly to produce. With ever-increasing demand for textile fibres and with cotton production almost reaching its peak, wood-based textile fibres may offer a suitable alternative. In 2019, only 6.4 percent of the global textile fibre market was man-made cellulosic fibres indicating an opportunity for growth. Finally, forests can provide many non-wood products with high economic value. For example, resins and derivates thereof are used to manufacture products in the chemical and food industries. Chemicals derived from resin generally have a smaller carbon footprint than their fossil-based equivalents, which could at least partially favour the substitution, of fossil-based chemicals.

There is strong evidence at product level that wood products are associated with lower GHG emissions over their entire life cycle when compared to products made from non-renewable or emissions-intensive materials. A review of 488 substitution factors obtained from 64 published studies indicates that the use of wood and wood-based products is generally associated with lower fossil and process-based emissions when compared to non-wood, functionally equivalent products. However, over three-quarters of studies in the literature focus on the construction sector and significantly less information exists for other traditional forest products such as paper for printing, writing, and packaging, or emerging forest products. Furthermore, most of the studies from which substitution factors could be derived focus on North America and the Nordic countries in Europe; substitution effects by wood products from many other areas of the world are not well understood, despite their relative importance in the global wood markets. The reviewed product-level substitution factors entail substantial variability and uncertainty, explained by differences in assumptions, data and methods. Indeed, the overall substitution factor for 95 percent of the values range between -1.1 kg C/kg C and +5.2 kg C/kg C. Substitution effects depend on the type of wood product being considered, the type of non-wood product that it substitutes, production technologies and efficiencies and the end-of-life management of wood and non-wood products, which can all vary between companies, regions and countries. Substitution factors reported in or derived from the international literature are context specific and generalizations are therefore not straightforward. The overall substitution effects also depend on the share of different forest products in the total product mix of a sector or country. There is still limited understanding of the substitution effects at the level of markets, countries or global regions, presumably due to limited information on end uses of wood and the difficulty in determining which materials are substituted.

While forest products can provide benefits compared to the use of non-renewable, GHG-intensive materials, there are also potential risks associated with the increased production and consumption of forest products. The production and extraction of raw materials needed to manufacture products has economic, social and environmental impacts. The increased use of forest products raises concerns regarding increased pressure on forests and forest-dependent people which, in case of unsustainable practices, could potentially result in the degradation of forests and ultimately in biodiversity loss and a reduction of carbon stocks and storage. To meet the needs of a growing population, sustainable, climate-smart forest management is needed, considering carbon emissions and removals by all carbon pools simultaneously to optimize longer-term and larger mitigation benefits, while supporting biodiversity and other ecosystem services. Existing life cycle analyses of forest products indicate that the processing, manufacturing, use and disposal of wood products has climate-related impacts, as well as other environmental impacts related to eutrophication, acidification, photochemical oxidant formation and human toxicity. However, in the context of substitution, it is important not only to look at the impacts of products made from wood, but also at the impacts of a functionally equivalent product made from other materials. Substitution effects on environmental impacts other than climate are not well understood.

Existing outlooks for the future production of wood products suggest a steady increase in the production of industrial roundwood for sawnwood, wood panels, paperboard and packaging over the coming decades, for alternative global developments. However, there are many uncertainties surrounding these outlooks for future forest product supply and demand, such as changes in consumer behaviour and the future market uptake of innovative wood products. A key question is whether and how substitution by wood products would result in additional demand for roundwood. However, there is still limited understanding on substitution effects at market-, country- and worldwide level. For a holistic understanding of the benefits of substitution by wood products, we must also consider the effects on carbon storage in forest biomass, soil and wood products, as well as their permanence and potential leakage effects. Allocating large volumes of wood to specific applications will likely increase competition for raw materials and may lead even to negative substitution effects, i.e. wood products are substituted by other (non-renewable) products.

There are various examples of eco-design, cascaded use or waste management of wood products that can improve the functioning of the circular bioeconomy. Paper recycling is one such example and experiences in collection and recycling can provide insights for other forest products. However, to strengthen the role that forest products play in a circular bioeconomy, there is a need to improve the manufacturing (including eco-design), use, reuse and recycling of forest products, and the management of residues and waste to reduce the environmental impact over a product's life cycle. To ensure the sustainability of a circular forest-based bioeconomy, it is important to develop awareness and overcome knowledge and implementation gaps along the global forest product value chain. To strengthen the contribution made by product substitution in a circular bioeconomy, recommendations are provided for specific actions that could be taken by the private sector, national governments, regional economic integration organizations, and through international cooperation bodies.

Among the 17 SDGs set by the United Nations (2015), Substitution of wood-based products for greenhouse gas-intensive products could contribute to a number of Sustainable Development Goals (SDGs), including SDG 12 (Responsible Consumption and Production), 13 (Climate Action) and 15 (Life on Land). In addition to the SDGs, six Global Forest Goals have been set to contribute to the progress on the SDGs. Among the six Global Forest Goals, substitution can play a role in

contributing to Global Forest Goal 2 (Enhance forest-based economic, social, and environmental benefits, including by improving the livelihoods of forest-dependent people).
Recommendations targeting the private sector:

- Focus on long-term responsible and sustainable production systems that contribute to achieving the Sustainable Development Goals.
- Contribute to the improved understanding of how environmental impacts of forest products compare with products made from other materials.
- Include sustainability considerations in the design of forest products that can remain in use as long as possible, aiming to take the environmental impacts of the products into account over their entire life cycle, and ensuring their reusability and recyclability.
- Provide transparent and accurate information on climate and other environmental impacts over the entire product life cycle.
- Invest to develop efficient production processes and technologies that optimize material use, prevent pollution, and reduce the environmental footprint of products.
- Foster the substitution of fossil-based or GHG-intensive products by wood products (or other bio-based products) by avoiding intra-sectoral competition where forest products compete with other environmentally beneficial products, and by encouraging intra-sectoral collaboration.

Recommendations targeting national governments and regional economic integration organizations:

- Incentivize and encourage responsible production and consumption of sustainable biobased products and discourage the use of non-renewable, fossil-based and GHG-intensive products.
- Consider the important role of forests and forest products in a functioning, circular bioeconomy, including carbon storage by forest ecosystems, carbon storage in wood products, product substitution effects and possible leakage effects.
- Exclude actions that favour climate change mitigation locally but lead to deforestation or forest degradation elsewhere as a result of international trade.
- Design and implement procurement procedures that prioritize sustainable products and services over other alternatives.
- Facilitate development of efficient systems to reuse and recycle (forest) products and avoid landfilling.
- Foster research activities to improve the understanding of substitution effects at product and market level for all product categories, all along the life cycle.
- Strengthen cooperation between scientific, industrial and financing actors to achieve shorter technological innovation cycles.
- Upgrade educational curricula at all levels to encourage sustainability thinking.
- Develop training and capacity building for professionals to update their knowledge of climate-smart and sustainable options.
- Improve consumer awareness by providing accurate and clear information on the possibilities and advantages of sustainable consumption patterns.

Recommendations targeting international cooperation bodies:

- Facilitate comparative studies and global data collection efforts for monitoring the bioeconomy to assess achievements and address knowledge and implementation gaps, to foster the transformation to a sustainable, circular bioeconomy.
- Facilitate knowledge exchange to strengthen the capacity of countries and the private sectors in the transformation to a sustainable, circular bioeconomy by sharing technical

knowledge, best practices, and innovations to mitigate climate change, prevent or reduce pollution, and to address other trade-offs.

- Promote international partnerships between academia, industry, finance, and public administration to explore how the transformation to a sustainable, circular bioeconomy could be achieved.


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1 Introduction

The global economy has been growing rapidly in recent decades. While the economic growth achieved has contributed to human prosperity and well-being, it has also led to the depletion of natural resources and services (Bongaarts, 2019), which raises the question about its sustainability. According to the International Resource Panel (IRP, 2020), the quantity of natural resources, such as biomass, fossil fuels, metal ores and minerals, extracted yearly increased twelvefold between 1900 and 2015. Nowadays, 74 percent of humankind's consumption is based on non-renewable natural resources, whose extraction, transportation, processing, use and disposal can cause major impacts on the environment, climate and biodiversity (IRP, 2020). Under existing trends, the global extraction of natural resources is estimated to increase from 84 billion to 184 billion tonnes per year between 2015 and 2050, going hand in hand with a considerable increase in greenhouse gas (GHG) emissions (Hatfield-Dodds *et al.*, 2017; IRP, 2020; Schandl *et al.*, 2018).

There is a growing understanding that we need to rethink the underpinning economic system to address the root causes of unsustainable natural resource use and achieve sustainable development. In the last decade or so, the concept of bioeconomy has gained importance and prominence as a means of tackling challenges such as the overconsumption of and overreliance on non-renewable natural resources (Aguilar, Twardowski and Wohlgemuth, 2019; Bell *et al.*, 2018; Birner, 2018; El-Chichakli *et al.*, 2016). While many definitions exist, the bioeconomy is generally considered to relate to the use of biological resources. Bio-based products can be substituted for fossil-based resources to produce energy, food, feed, fibre and other manufactured goods, and the application of biological processes (i.e. biotechnology) for manufacturing goods. The development of the sustainable bioeconomy is seen as one way of reaching the Sustainable Development Goals (SDGs) (El-Chichakli *et al.*, 2016; Heimann, 2019) that were adopted by the world's leaders in 2015 and that aim to "free humanity from poverty, secure a healthy planet for future generations, and build peaceful, inclusive societies as a foundation for ensuring lives of dignity for all".

Understanding of the concept of bioeconomy is evolving. While the earlier understanding focused more narrowly on resource substitution, natural capital and biotechnology (Birner, 2018; D'Amato *et al.*, 2017), more recently, understanding of the concept has broadened to encompass sustainability, services and circular economy aspects (European Commission, 2018b; Global Bioeconomy Summit, 2020; Hetemäki *et al.*, 2017; Palahí *et al.*, 2020). Particularly with respect to circularity, the bioeconomy concept has been linked with a related concept of circular economy (Hetemäki *et al.*, 2017), which focuses on processes for decoupling resource use and economic output and highlighting the end-of-life stage of a product as opposed to traditional linear economic models that assume infinite supply of resources (D'Amato *et al.*, 2017; Reichel, De Schoenmakere and Gillabel, 2016). A circular bioeconomy can provide a conceptual framework for using renewable natural capital to transform and manage land, food, health, and industrial systems holistically with the goal of achieving sustainable well-being in harmony with nature (Palahí *et al.*, 2020). Forests and forestry form a core part of the bioeconomy. Forests are natural systems that provide a multitude of ecosystem goods and services, such as raw materials, climate regulation, carbon storage, biodiversity, and various non-wood forest products (NWFPs), which constitute important contributions to economy (Salzman *et al.*, 2018). With increasing societal pressure to reduce GHG emissions and greater demand for more renewable and sustainable products, part of the forest industry is moving towards the production of new bio-based products that can meet these demands (Hurmekoski *et al.*, 2018; Lettner *et al.*, 2018) This change is shaped by new technologies and products that aim to decrease the carbon footprint of products and processes, while tackling pollution and waste generation. Such products can include textiles, wood-based composites, fuels, chemicals, and packaging (Hurmekoski *et al.*, 2018; Kröger, 2016; Sahoo *et al.*, 2019; Stern *et al.*, 2018). The forest sector has significantly contributed to the development of these clean technologies and bio-based products that have high potential for substituting fossil-based materials (Hetemäki *et al.*, 2017; MacRae and Harnett, 2019; Nighbor, 2018).

In the context of climate change, the forest-based sector can contribute to climate change mitigation through (i) carbon storage in forest biomass and soil; (ii) carbon storage in wood products; and (iii) material substitution. When wood is harvested and products made from it, carbon remains stored in these products depending on their end use and lifetime. The contribution to climate change mitigation achieved through carbon storage in wood-based products can be increased by expanding the quantity of these products through additional harvest (Johnston and Radeloff, 2019; Pilli, Fiorese and Grassi, 2015) and by extending the products' lifetime and increasing recycling or cascade use (Brunet-Navarro, Jochheim and Muys, 2017; Jasinevičius *et al.*, 2017; Xu *et al.*, 2018). The contribution to climate change mitigation through material substitution involves the use of wood for different applications, such as buildings or textiles, instead of other materials (e.g. concrete, steel, plastics and synthetic fibres) to avoid or reduce GHG emissions associated with the production, use and disposal of the products (Geng *et al.*, 2017; Leskinen *et al.*, 2018; Sathre and O'Connor, 2010). In addition to wood-based products, other forest products can also play an important role in a functioning bioeconomy. For example, NWFPs and fuelwood are very important for people's subsistence in many parts of the world (Angelsen *et al.*, 2014; FAO, 2014; Lovrić *et al.*, 2020). In fact, about half of the world roundwood production goes to fuelwood rather than industrial (material) purposes (FAOSTAT, 2020).

This report addresses the role of forest products in replacing fossil-based and GHG-intensive products and explores ways of increasing the contribution of substitution by forest products to sustainable development. To that end, the report first reviews understanding of the bioeconomy and the role of forest products across the world (Chapter 2). Second, it presents examples of conventional and innovative forest products and describes their role in the bioeconomy (Chapters 3 and 4). Third, it examines the quantitative and qualitative understanding of the environmental impacts and benefits of substituting fossil-based or GHG-intensive products with forest products, and of the contribution made by substitution to achieving SDGs (Chapter 5). Fourth, the report outlines current understanding of the future global supply and demand dynamics of forest products and the potential impacts that increased substitution may have on these dynamics (Chapter 6). Fifth, it identifies gaps in the global forest product value chain (Chapter 7) and finally, Chapter 8 provides key conclusions and recommendations.


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2 Status of country efforts related to a forest-based bioeconomy

The bioeconomy can be defined and interpreted in many different ways. The International Advisory Council on Global Bioeconomy (2020) defined the bioeconomy as "*the production, utilization, 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*". A common feature in the many definitions of the bioeconomy is that they relate to the use of biological resources, which can be used to substitute fossil-based resources for producing energy, food, feed, fibre, and other manufactured goods. This chapter introduces the understanding of the bioeconomy and the role of forest products around the world. It describes the efforts made by several countries or regional economic integration organizations, which were selected to cover different parts of the world, considering the importance of their forest sector and the different governance systems. A summary of the key characteristics of bioeconomy efforts is provided in Table 2.1, while more detailed profiles are provided in Appendix 1.

Policies dedicated or related to the bioeconomy have been launched around the world. For the most part, such policy efforts are bioeconomy related but not bioeconomy focused (Bioökonomierat, 2019). For instance, in the United States of America, Brazil and New Zealand, specific policy measures exist to tackle bioeconomy development. In the United States of America, a bioeconomy strategy called the National Bioeconomy Blueprint (The White House, 2012) sets out objectives on strengthening research and development, fast-forwarding innovations from laboratory to market roll-out, and reducing regulatory barriers, among others. In Brazil, an Action Plan for Technology and Innovation on Bioeconomy was established to foster innovation and provide conditions for the strategic insertion of the Brazilian bioeconomy within the global scenario, among other objectives (MCTIC, 2018). Other countries such as China, Turkey or Ghana do not have a dedicated bioeconomy policy or strategy but do have policies that are related to bioeconomy development. For instance, Turkey promotes the bioeconomy through its Biotechnology Strategy and Action Plan (2015–2018). Hence, all the countries and regions covered in this review have either dedicated or related policies in place for developing the bioeconomy. Some have focused efforts in specific sectors, while others have let the bioeconomy develop more organically.

At an overarching level, the objectives of the strategies and policies are often linked with job creation, sustainable socioeconomic development, and sustainable management of natural resources. Many of the existing bioeconomy-focused or bioeconomy-related policies relate to innovation and biotechnology to develop new value-added products (e.g. chemical, packaging, biofuels, pharmaceuticals) or improve the productivity of biological resources and bioenergy. In the Russian Federation, for instance, a State programme for the development of biotechnology (BIO2020) was created to modernize the country's economic sectors, including targets to foster the development of biotechnology in several areas (Government of the Russian Federation, 2012). One of the priorities related to the bioeconomy in Ethiopia is food security, which is, in comparison, an uncommon issue in the bioeconomy-relevant policy measures in the other countries reviewed. Such differences reflect the flexibility and broad coverage of possible issues that form the bioeconomy concept.

Table 2.1. Bioeconomy efforts in selected countries and regional economic integration organizations

Global region or country	Relevant strategies, action plans and other efforts	Priorities	Target sectors	Key areas from forest-based bioeconomy perspective
Australia	No bioeconomy-specific strategy, but related policies at national and sub-national levels	Sustainable economic growth and job creation, particularly in rural areas	Agriculture, bio-based chemicals and packaging, biofuels and bioenergy, forestry, pharmaceuticals	Bioenergy
Brazil	Bioeconomy-related strategies: National Strategy for Science, Technology and Innovation (2016) Action Plan for Technology and Innovation on Bioeconomy (2018)	Social and environmental benefits, economic growth, development of biotechnology industry	Not specific to any sector, but traditionally focused on agriculture	Biotechnology
China	Bioeconomy-related strategies: Chinese National Strategy (2007)	Development of biotechnology, environmental protection, and biosecurity	Bioenergy, agriculture	Biotechnology (biomedical products, biochemicals, bioenergy)
Ethiopia	Bioeconomy-related strategies: Climate-Resilient Green Economy strategy (2011–2025) Growth and Transformation Plan	Forest management, biotechnology development, job creation and food security	Bioenergy, agriculture	Bioenergy and biotechnology
European Union	Bioeconomy-specific strategy: Innovating for Sustainable Growth: a bioeconomy for Europe (2012) Updated Bioeconomy Strategy (2018): A sustainable Bioeconomy for Europe	Strengthen the connection between economy, society, and the environment	Biorefineries and value-added sectors relying on agriculture, forestry, fisheries and aquaculture	Traditional forest products (e.g. sawnwood, pulp and paper, ecosystem services, etc.) and new products (e.g. chemicals, plastics, mass timber products, textiles, bioenergy including biofuels, etc.)

Global region or country	**Relevant strategies, action plans and other efforts**	**Priorities**	**Target sectors**	**Key areas from forest-based bioeconomy perspective**
Ghana	Bioeconomy-related strategies: Bioenergy policy Ghana Shared Growth and Development Agenda I and II Accelerated Agricultural Growth and Natural Resource Management Forestry Development Master Plan Renewable Energy Act	Energy security, food security, biotechnology development, rural development, fossil fuel import substitution, sustainable management of forest resources	Bioenergy, agriculture	Bioenergy and biotechnology
New Zealand	Bioeconomy-specific strategy: Primary Sector Science Roadmap – Te Ao Tūroa (2017)	Adding value to the primary sector and enhancing the sector's international competitiveness	Bio-based primary sector industries	Climate change mitigation, bioenergy, value addition, biotechnology development and utilization
The Russian Federation	Bioeconomy-related strategies: State Programme for the Development of Biotechnology Bioindustry and Bioresources platform (BioTech2030)	Modernization of the economic sectors	Bioenergy Wood industries	Bioenergy and biotechnology Sustainable transformation of bio-based resources
Turkey	Bioeconomy-related strategies: Biotechnology Strategy and Action Plan (2015–2018)	Social and environmental benefits, support to rural development, economic growth, sustainability of ecosystem services	Health, agriculture	Biotechnology
United States of America	Bioeconomy-specific strategy: National Bioeconomy Blueprint (2012) Energy Policy Act (2005) Agricultural Improvement Act (2018) BioPreferred Program (2002 and expanded in 2018)	Strengthen research and development, job creation	Bioenergy, agriculture life sciences and biotechnology	Innovative wood products (construction sector, advanced biofuels, renewable chemicals, and other bio-based products)

Regardless of whether a country has a dedicated bioeconomy policy or strategy or promotes the bioeconomy through other relevant policies, there are differences with respect to the focus and role of forests and forest products in the bioeconomy. The role of forests and the forest sector is not always clearly acknowledged in bioeconomy or related strategies and action plans. This is the case in Turkey and China, for example, where the bioeconomy is more focused on agriculture. On the other hand, the European Union and Australia, among others, consider the forest-based bioeconomy in their policy documents. For instance, the European Union's updated Bioeconomy Strategy comprises traditional forest products, including forestry, wood products, pulp and paper, along with novel or new sectors, products and applications developed (e.g. the chemical industry, construction, pharmaceuticals, energy), and ecosystem services (e.g. hunting, recreation, and water purification) (Lier *et al.*, 2019; Ronzon *et al.*, 2020). Generally, the target sectors of the bioeconomy most often referred to by the countries reviewed are agriculture and bioenergy.

When zooming in on the key areas in the countries reviewed from a forest-based bioeconomy perspective, further similarities and differences can be observed. Biotechnology and bioenergy are common themes linked with the forest-based bioeconomy across the countries. Apart from those areas, however, the countries emphasize different issues in slightly different ways. For instance, New Zealand mentions climate change mitigation and value addition to the sector, while the United States of America sees innovative wood products as a key area. Among other things, the focus of the forest-based bioeconomy can differ according to the importance of the forest sector in the countries.

Take-home messages

- Understanding of the concept of the bioeconomy and the role of forest products varies significantly between countries around the world, and the concept continues to evolve over time.
- The status and development of bioeconomy-related policies and implementation efforts vary greatly between countries; some have focused efforts in specific sectors, while others have let the bioeconomy develop more organically. Some countries do not have any bioeconomy or related strategy.
- Many of the existing bioeconomy strategies relate to innovation and biotechnology to develop new value-added products (e.g. chemical, packaging, biofuels, pharmaceuticals) or improve the productivity of biological resources and bioenergy, while aiming at job creation.
- Forests and the forest sector have an important role in the bioeconomy, but this role is not always clearly defined in bioeconomy (or bioeconomy-related) strategies and action plans.

3 The role of selected forest products in the bioeconomy

The forest sector is an important element in a bioeconomy. The sector has long been manufacturing conventional forest products that are part of people's lives such as houses, furniture, the numerous types of paper products, as well as lesser-known materials such as chemicals and cellulose-based fillers (Mäntyranta, 2020a). During the manufacturing process of many of these conventional products, residues are produced. In most cases, these have been used to generate energy for the industry. However, some of the residues and by-products have functional properties and can be used as feedstock in the production of value-added products. New branches in the value chain are being created with the inclusion of integrated biorefineries (Figure 3.1) as a result of the forest industry's growing interest in using residues and by-products as feedstock for value-added products, in developing new technologies and expanding their product portfolio. In addition, the population is increasingly interested in accessing products with a lower negative impact on the environment and that represent solutions to problems caused by the extensive use of non-renewable materials and dependence on fossil sources. This chapter presents some of the conventional forest products that have an important place in the bioeconomy, while Chapter 4 showcases some of the innovative forest products that will reach the market in the near future or that are gaining momentum.

For some forest product groups, significant changes have occurred in product development and/or due to structural changes in demand (e.g. Hurmekoski and Hetemäki, 2013; Johnston and van Kooten, 2016; Latta, Plantinga and Sloggy, 2016). For example, important changes have occurred in the production and consumption of newsprint and printing paper, because of digital media reducing demand for them. This contrasts with wrapping and packaging materials, which have seen rising demand due, among other things, to increased e-commerce sales. Similarly, wood-based construction is seeing a small revolution through the development of high-rise buildings using engineered wood products. Textile markets are also seeing increased use of dissolving pulp once again, after its world production peaked in 1974 and subsequently declined until 2001. World dissolving pulp production is now at a historically high level at around 8 million tonnes. In addition, new technologies to produce more environmentally friendly dissolving pulp have been developed in recent years, and this may lead to market expansion. Besides the previously mentioned products, a range of chemical derivates from forest biomass can be used for bioplastics, biofuels and other products. These new developments have impacts on the demand for roundwood, though some products are manufactured from recycled materials, by-products (e.g. sawdust, wood chips, and black liquor from pulping) or from forest residues (Hurmekoski *et al.*, 2018). Raw materials that, at best, had low-value applications in the past are now being turned into more sophisticated, value-added products (see Box 1). This chapter describes market trends, as well as key drivers for production and demand of the following forest product groups:

- Graphic paper
- Traditional wrapping and packaging
- Wood products for construction
- Man-made cellulosic fibres for textiles
- Resin and its chemical derivates.

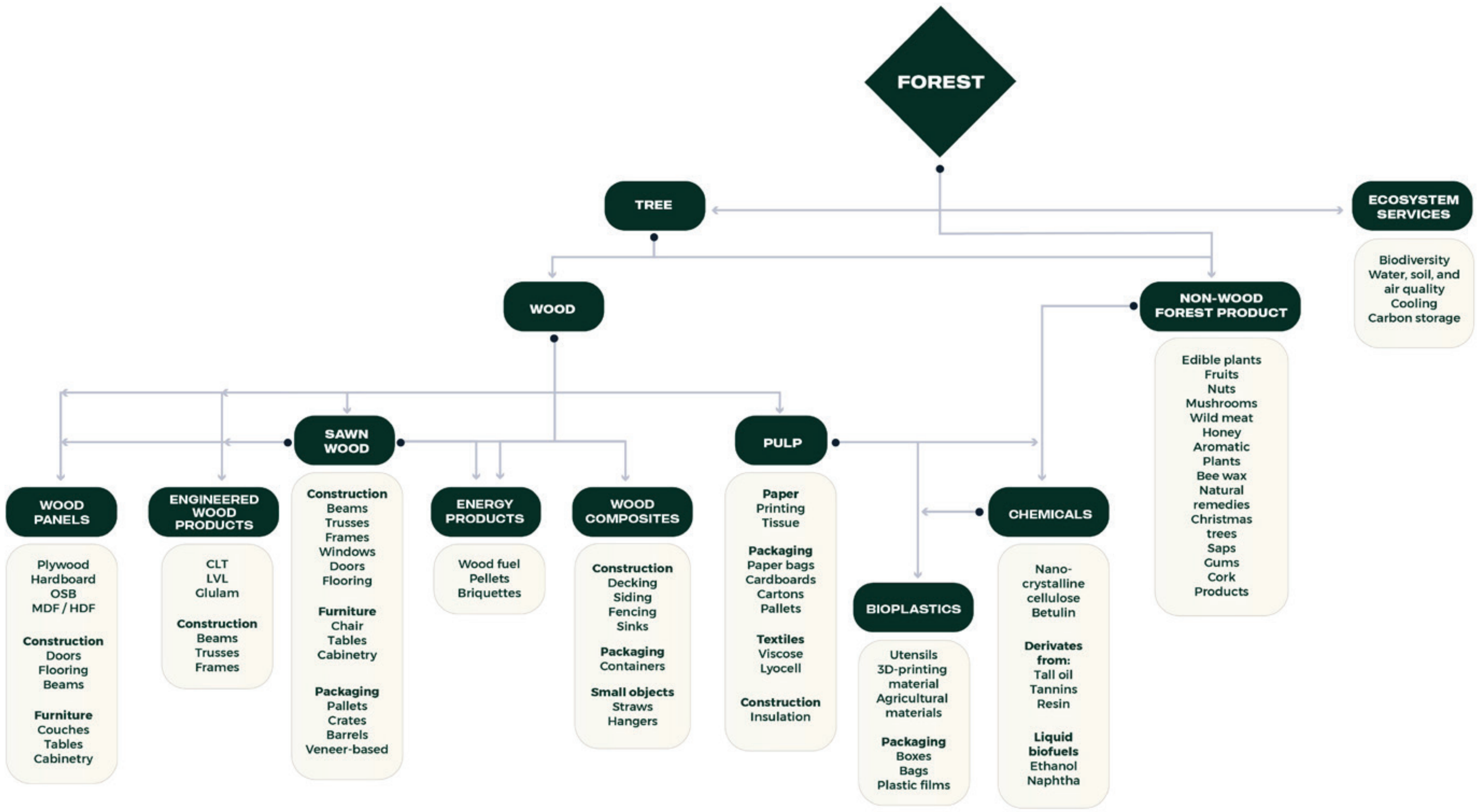

Figure 3.1. Typical forest product utilization pathways

Box 1: Wood-based medical products

The global COVID-19 pandemic has directed significant public attention to various medical products and their availability. At the same time, supply has struggled at times to meet the sudden surge in global demand for these products. According to one estimation, global sales of masks and respirators will exceed pre-pandemic estimates by 211 percent and 305 percent, respectively by 2025 (Life Science Intelligence, 2020). However, production capacities for such products and the materials traditionally used for them have proven inadequate, which has led to supply shortages. For instance, in the global face mask value chain, a major bottleneck amidst the pandemic has been the limited supply of nonwoven fabric manufactured with polypropylene (OECD, 2020a).

It is possible to produce various medical products from renewable, wood-based materials, such as wood fibre or wood tar. For example, disposable gowns, surgical drapes, medical bed covers and hospital bed sheets are commonly made of nonwoven polypropylene. Such products can also be made using a wood pulp nonwoven fabric, which comprises 55 percent high-quality wood pulp and 45 percent high-quality polyester fibre with an advanced wood pulp spun lace complex technology (Henan Lantian Medical Supplies, 2019). A paper membrane, made of highly crystalline cellulose nanofibres, is capable of filtering virus particles and is a promising bio-based solution for reducing the prevention of spreading viruses (Metreveli *et al.*, 2014). The manufacture of various medical supplies, such as surgical masks and gowns, is enabled through a particular grade of wood pulp made from western red cedar that produces a soft fibre, making it suitable for these types of products (Bush, 2020). Compared to polypropylene-based medical products, wood-based products have the added advantage of being biodegradable. This can be a valuable attribute in avoiding environmental pollution caused by, for example, discarded, disposable face masks, the use of which has increased because of the pandemic. For instance, researchers have recently developed a fully compostable and biodegradable medical mask made of wood fibre (University of British Columbia, 2020).

For its binding, strength and absorbent qualities, wood is suitable for and found in several medical and hygiene products, such as hygiene papers, hand sanitizers, soaps, toothpastes and diapers (Rayonier, 2020). In addition, wood-based products other than those based on wood fibre can be suited to medical and hygiene applications. For instance, topical pine tar can be used to treat a range of skin conditions thanks to its antiseptic, anti-inflammatory, antibacterial and antifungal properties, for example, in the form of soap-free bars (Barnes and Greive, 2017). Also, wood is found in many pharmaceuticals in the form of cellulose ether, which can serve toward binding the contents of a pill, acting as a thickening agent in liquid medicines, or functioning as the hard outer coating of tablets, among other uses (Rayonier, 2020). Research has also been carried out into producing pharmaceutically relevant compounds from wood chips, which results in water as the only waste product as opposed to hazardous waste in more typical production methods (Elangovan *et al.*, 2019). Finally, there have been some advances in the development of low-cost wound dressings made of wood-based nanocellulose, improving the competitiveness of this forest product in this market segment (Claro *et al.*, 2020; UPM, 2020).

3.1 Graphic paper

Product definition

Graphic paper is an aggregate category of paper products used for communication purposes, consisting mainly of printing and writing papers (e.g. office paper, books and magazines) and newsprint (used mainly for newspapers) (FAO, 2019a). The use of pulpwood to manufacture graphic paper products dates back to the late nineteenth century and is also associated with a long tradition of recycling: back in 1961, recovered paper already amounted to around 15 million tonnes (FAOSTAT, 2020). As a result, collection systems are well advanced, particularly in developed countries. In the United States of America and Europe, for instance, 66–67 percent of all paper and paperboard was recovered in 2018 (FAO, 2019b), with some individual countries reaching recovery rates of up to 80 percent overall (Haggith *et al.*, 2018).

Use of recovered fibre/wood in manufacturing

Despite the large share of recycled paper and paperboard in some regions, there are great differences in the degrees to which recovered materials are used in the production of various paper grades. Data covering 36 countries, representing over 70 percent of the world paper and paperboard production, suggests that in 2009, 18 percent of the feedstock for newsprint was recovered materials and 4 percent in the case of printing and writing paper (FAO, 2010). More recent data, which is not fully comparable, indicates an upward trend for recycling rates (FAO, 2019a). However, it should be noted that profit incentives encourage the global trade of recovered paper (Mansikkasalo, Lundmark and Söderholm, 2014), which may not be as environmentally sustainable as reprocessing wastepaper in the country in which it was produced (Staub, 2020).

Market situation

Global newsprint production increased steadily up until 2004, where it peaked at around 40 million tonnes. After that, global production significantly decreased to the point that, by 2019, it had dropped to approximately 18 million tonnes (FAOSTAT, 2020). A similar trend can be seen for printing and writing paper: long and steady growth that ended in 2007, when global printing and writing paper production peaked at approximately 116 million tonnes. In 2019, production had fallen to around 92 million tonnes (FAOSTAT, 2020). Thus, world graphic paper production has been declining for about 15 years, although the consumption of certain paper products (e.g. newsprint) had already started to drop in the world's biggest market – the United States of America – in 1987 (Hetemäki, 2005).

Regional differences in graphic paper consumption and production have been significant (Hetemäki, Hänninen and Moiseyev, 2013). Figure 3.2 shows production trends in Asia, Europe and North America, which accounted for an average 95 percent of global graphic paper production from 1961 to 2018 (FAOSTAT, 2020). The decline in graphic paper production started in North America, quickly followed by Europe. In Asia, printing and writing paper production has stabilized over the last three years and we can see a decline of newsprint production.

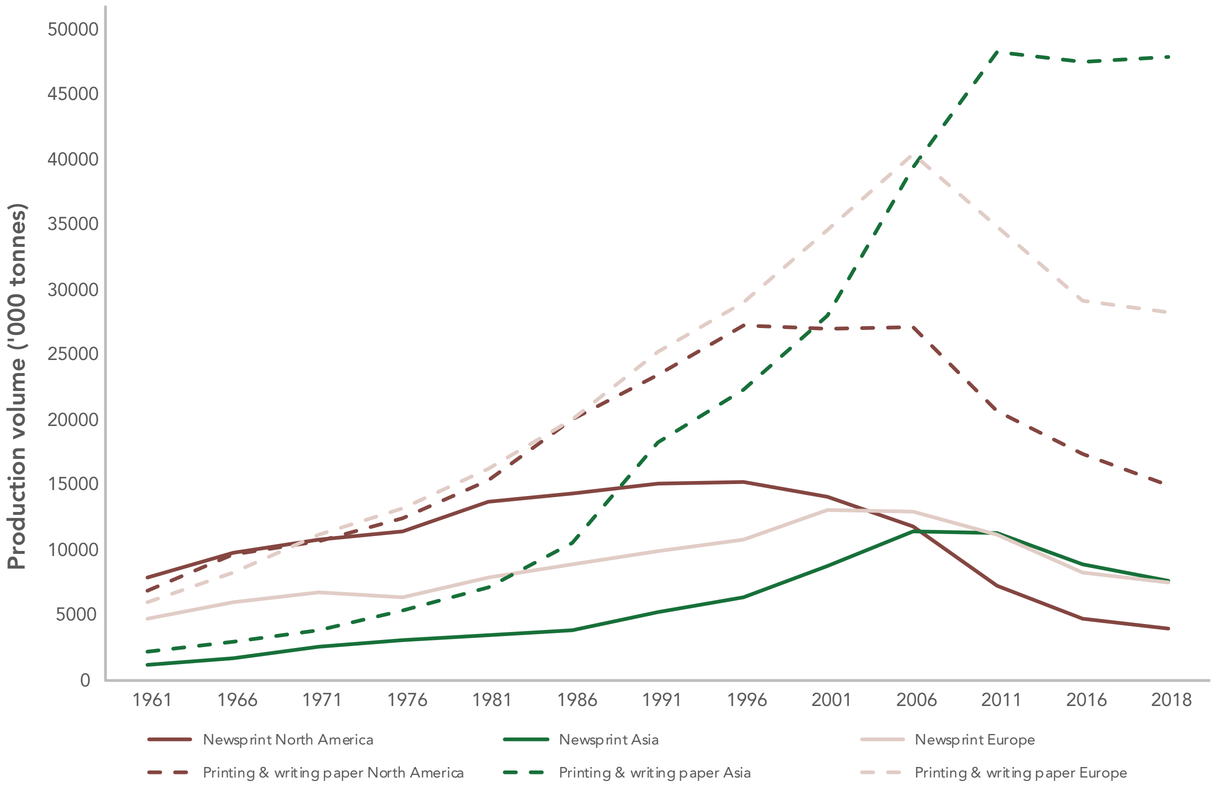

Figure 3.2. Trends in newsprint and printing and writing paper production in the major world production regions

Source: FAOSTAT (2019)

Market drivers and forecasts

The link between increasing graphic paper production and consumption and growth in consumers' income no longer appears valid: at a certain income level, any further income growth is now associated with decreasing graphic paper production. Digital media is the main factor contributing to the decline in graphic paper production and consumption (Chiba, Oka and Kayo, 2017; Hetemäki, 2005; Hetemäki, Hänninen and Moiseyev, 2013; Latta, Plantinga and Sloggy, 2016; Rougieux, 2017). Considering continued growth in internet adoption rates, it has been projected that, compared to 2012 production levels, global newsprint consumption could be 34–37 million tonnes lower and global printing and writing paper consumption 77–87 million tonnes lower by 2030 than in forecasts in other studies that do not account for internet use (Johnston, 2016). This could mean some 229–259 million cubic metres of roundwood equivalent (RWE) would become available for other uses (Ervasti, 2016; FAO, 2019a). As for regional differences, newsprint production in North America could be 78 percent lower in 2030 compared to 2012 production levels, 43–59 percent lower in Asia, and 49–58 percent lower in Europe (Johnston, 2016). For printing and writing paper, production could be reduced by 75–80 percent, 17–31 percent, and 27–33 percent by 2030 in North America, Asia and Europe respectively (Johnston, 2016).

3.2 Traditional wrapping and packaging

Product definition

The traditional wrapping and packaging category includes paper and paperboard used for wrapping and packaging purposes, namely: case materials (used mainly in the manufacture of corrugated board), cartonboard (used mainly in cartons for consumer products, such as frozen food and liquid containers), and other wrapping and packaging (all papers and boards used for packaging purposes other than case materials and cartonboard) (FAO, 2019a). Such traditional wrapping and packaging materials have been manufactured and used since the nineteenth century and, by the early 1900s, shipping cartons of double face corrugated paperboard began to replace wooden crates and boxes used for trade (Hook and Heimlich, 2017).

Use of recovered fibre/wood in manufacturing

Like graphic paper, wrapping and packaging materials are recovered at high rates especially in developed countries (Haggith *et al.*, 2018), and these products are also highly recyclable. The fibre length and stability properties of corrugated board can withstand up to 25 recycling cycles (Putz and Schabel, 2018). According to data from 36 countries representing 70 percent of global paper and paperboard production in 2009, recovered paper accounted for 42 percent of the feedstock for case materials production, 6 percent for cartonboard production, and 13 percent for the production of other wrapping and packaging (FAO, 2010). More recent data from 2017 suggests increased recycling rates, although the datasets are not fully comparable (FAO, 2019a).

Market situation

Globally, wrapping and packaging represented 59 percent of all paper and paperboard production in 2018 (FAOSTAT, 2020). It is thus the single most important paper product segment in terms of production quantity. In 2018, case materials represented 66 percent of the production quantity in major production regions, cartonboard 22 percent, and other wrapping and packaging 12 percent (FAOSTAT, 2020). Between 1961 and 2018, wrapping and packaging production grew overall in North America, Asia and Europe, which represented 94 percent of global wrapping and packaging production over that timespan (Figure 3.3). However, Figure 3.3 shows that growth was much stronger in Asia and that, in 2018, it accounted for 50 percent of production in the three regions. Figure 3.4, Figure 3.5 and Figure 3.6 show the production trends for case materials, cartonboard and other wrapping and packaging in North America, Asia and Europe respectively (representing 92 percent of global production) from 1998 to 2018. The picture is similar for case materials and cartonboard: production in Asia is growing much stronger than in the other regions, making it the most important production region in terms of quantity. Meanwhile, the production of other wrapping and packaging is decreasing in North America and slightly increasing in Asia and Europe.

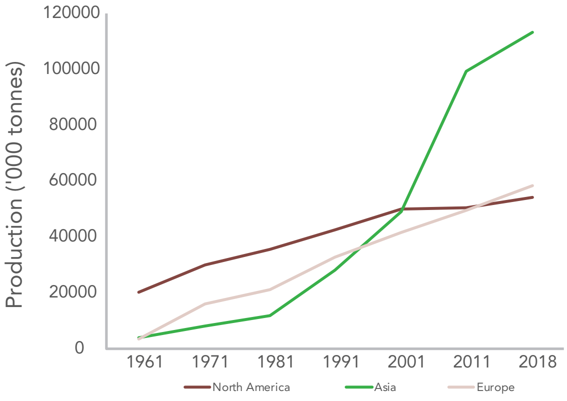

Figure 3.3. Wrapping and packaging production in major world production regions

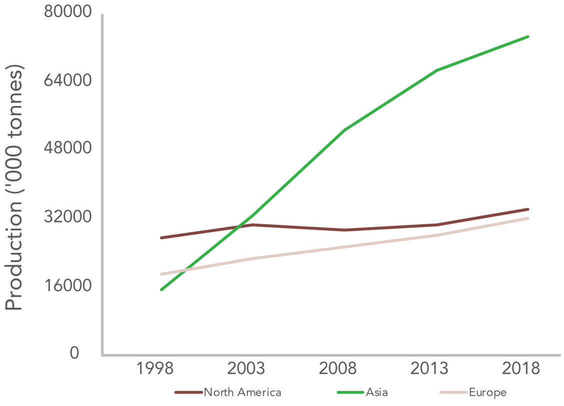

Figure 3.4. Case materials production in major world production regions

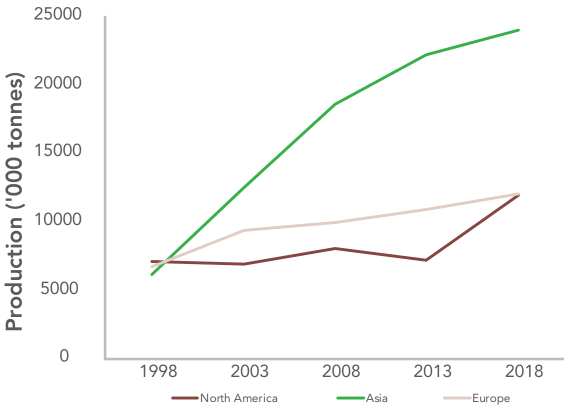

Figure 3.5. Cartonboard production in major world production regions

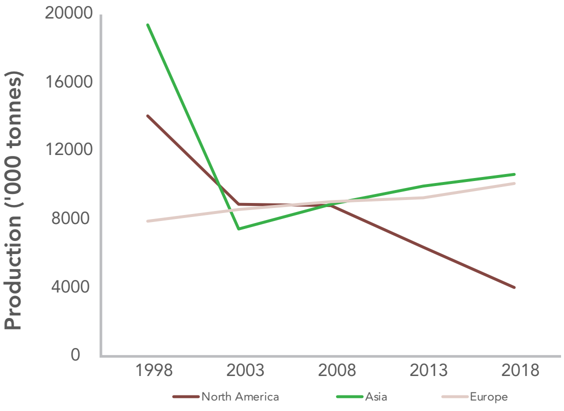

Figure 3.6. Other wrapping and packaging production in major world production regions

Source: FAOSTAT (2020)

Market drivers and forecasts

Global population and income growth are driving – and are expected to continue to drive – the overall upward market trend for wrapping and packaging production (Berg and Lingqvist, 2019; Hurmekoski *et al.*, 2018). This is associated with the ever-growing consumption of goods and the need to package them for transport and sale. Additionally, e-commerce and demand for take-away products is contributing to the growth of wrapping and packaging markets (Berg and Lingqvist, 2019; Hurmekoski *et al.*, 2018; see also Box 2). This is particularly so in Asia with most of the world population and growing income levels. For example, China's cardboard consumption in 2019 was still just 10 kilograms per capita compared to 40 kilograms per capita in the United States of America (Metsä Fibre, 2019). There is some uncertainty for future market trends due to plastic packaging alternatives; discussions over the need to reduce plastic packaging waste could prove beneficial for wood fibre-based wrapping and packaging for sustainability reasons, while lightweight plastic packaging could have a competitive advantage over their wood fibre-based counterparts for logistics reasons (Barker, 2018; Berg and Lingqvist, 2019).

Box 2: The impact of COVID 19 on traditional wrapping and packaging

The COVID-19 pandemic resulted in government enforced lockdowns all around the globe. Because of this, traditional brick-and-mortar retail was largely forced to shut down. The situation prompted a rapid shift in consumer preference towards online shopping, which persisted even after lockdowns ended. For example, a global survey of 6 200 brand and retail sites showed that year-on-year percent growth of shopping activity – in terms of page views – in 2020 was 11 percent in January, reaching 88 percent in April and still 75 percent in June (Hottenroth, 2020). Even when total consumer spending had fallen due to COVID-19, the change in consumer behaviour favouring e-commerce was expected to outlast the pandemic (United Nations Conference on Trade and Development (UNCTAD), 2020). Commerce also responded to the changes, as new players and products emerged on the e-commerce landscape (OECD, 2020b).

This trend has fuelled the existing growth in demand for traditional wrapping and packaging induced by e-commerce (Garland, 2020). As a specific effect of the pandemic, consumer demand for online grocery shopping and take-away products, which are packaged in corrugated board, has risen (Safe Load Testing Technologies, 2020). Observers also note that the pandemic has had an impact on the recycling of traditional wrapping and packaging materials, as increasing consumption of the materials contributes more feedstock for the recycling sector. However, in the United States of America, for example, the volume shift from commercial to residential recycling is resulting in higher contamination rates of materials and thus lower volumes and recycling rates overall (Crunden, 2020). In general, the impact of the pandemic on the traditional wrapping and packaging sector is playing out dynamically, but overall the sector has proven resilient so far.

Traditional wrapping and packaging are based on renewable resources and can be recovered and reused within existing infrastructure and systems in many parts of the world. While this segment competes with other materials for wrapping and packaging purposes, such as plastics (Barker, 2018), no substitution relationship exists between traditional wrapping and packaging and plastic packaging (Chiba, Oka and Kayo, 2017). This may be because the overall market for packaging materials is growing and there is demand for both types of packaging materials. Moreover, for some applications, traditional wrapping and packaging may be more suitable, while plastic packaging may be more suited for other uses (Barker, 2018), which indicates that both categories could have their own market segments with no – or with limited – possibility for substitution. Nonetheless, traditional wrapping and packaging could be the more sustainable option when compared to fossil-based plastic packaging over a product's life cycle (Barker, 2018; Hurmekoski *et al.*, 2018), although more research is needed on this (Leskinen *et al.*, 2018), including with respect to novel packaging materials, such as bioplastics.

3.3 Wood products for construction

Wood is one of the most traditional materials used in construction. Nowadays, there is quite an extensive choice of wood products for this purpose, from sawnwood to engineered products. The most popular wood construction system is arguably the light-frame system, which uses dimensional lumber and engineered wood products placed at regular intervals and fastened together to create floor, wall, stair and roof assemblies (naturally:wood, 2020). This construction system is commonly used in single-family, multifamily, commercial and light industrial buildings, due to its cost advantages, availability and ease of assembly (Think Wood, 2020). Because the structural elements are increasingly prefabricated offsite – and frequently shipped to the site ready with plumbing, electrics, paint, flooring, etc. – the cost and time to complete the construction are lower than traditional systems (Think Wood, 2020; Wood Works, 2014).

Wood construction is not equally developed around the globe, and is mostly found in the Nordic countries, North America, Australia, Japan and parts of southeast Asia (Swedish Wood, 2020). In developing countries, wood is still seen as a traditional construction material (FAO-ACSFI, 2020) and there are many constraints that hinder widespread adoption of this material. Some of the constraints on broader use of wood in construction are:

- misconceptions among consumers, who see wood as a low-quality material or associate it with deforestation;
- higher costs, when using engineered wood products or more modern construction systems;
- the lack of specialized labour, as construction workers are used to brick-and-mortar construction systems;
- the lack of connection between actors in the value chain; and
- the lack of specific legislation and standardization (Shigue, 2018).

Despite that, some changes can already be seen, especially in developing countries with extensive forest areas. In Brazil, for example, the number of companies that produce engineered wood products has been increasing, albeit slowly, and there is a closer connection between the civil engineering and the forest sectors, resulting in more wood constructions (Shigue, 2018).

Product definition

Compared to many manufacturing industries, there have been few major improvements over the past few decades in the productivity, profitability or the environmental impact of construction. However, driven by institutional changes, promotion campaigns and technological development in the 1990s, novel industrial wood-frame multistorey construction practices have been emerging, first in European countries (Hurmekoski, Jonsson and Nord, 2015) then spreading to other regions, driving demand for engineered construction materials.

Engineered wood is a term used for an assembly of composite products such as beams and planks, which are usually made of wood boards, veneer layers, wood shavings, or wood chips. The wood units are put together in various manners, such as finger joints or other types of mechanical joining, usually with additional fixation provided by glue, or by simply gluing wood units together, or by moulding units (such as sawdust, chips or pulp) into shape using mechanical pressure with or without additional adhesives. A wide variety of engineered wood products has been developed relatively recently and they are increasingly finding applications in building construction. Examples of established and emerging engineered wood types are: finger-jointed solid construction timber, glued solid timber, glued laminated timber (glulam), light composite wood-based beams and columns, (I-beams or double T-profiles), parallel strand lumber, cross-laminated timber (CLT), and laminated veneer lumber (LVL) (Figure 3.7).

Recently, most attention has focused on the uptake of CLT and glulam in building construction, a trend that started in Europe under the impetus of high-rise construction and the increasing uptake in prefabricated (residential and non-residential) construction. The high degree of customization and application of wood for nearly any building part, including load-bearing structures, is revolutionizing the wood construction sector. Together with the construction sector's adoption of engineered wood, there is a lot of attention on waste reduction in the construction process, the development of modular prefabricated construction techniques, and ease of disassembly in the end-of-life stage.

Use of recovered fibre/wood in manufacturing

One benefit of engineered wood products is that in some applications, wood of smaller dimensions – that would not traditionally be used as sawnwood – can be combined into larger composite lumber pieces, thereby opening up the range of applications for lower grade wood. However, the most important qualities of engineered wood in construction applications are their structural and dimensional stability, the increased dimensions that can be achieved, and the speed at which prefabricated construction elements can be assembled at the construction site, thereby dramatically reducing the time needed to complete construction.


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Glued solid timber

Glued solid timber consists of lamellae of the same strength class or manufacturer-specific strength class, which are bonded together, comprising up to five lamellae with thickness from 45 mm to 85 mm. The total cross section of the beam shall not exceed 280 x 280 mm. Glued solid timber is predominantly bending stressed (upright position of the square wood). The lamellae of glued solid timber are classified into strength classes by visual or machine grading.

Glued laminated timber (glulam)

Glulam is manufactured from bonded lamellae with parallel fibre orientation. There are at least two lamellae 6 mm to 45 mm thick. The timber is planed and classified into strength classes by visual or machine grading. Spruce, fir, pine, and larch are most commonly used. Particularly suited for components bearing high stresses or spanning large distances which must satisfy stringent requirements with respect to dimensional stability and appearance. Straight as well as curved beams can be manufactured.

Parallel Strand Lumber (PSL)

PSL is a product manufactured with 3 mm thick and 15 mm wide veneer strips. The strips can be up to 2.6 m long before the strips are bundled together with their individual ends offset and with fibres primarily oriented parallel to the major axis of the beam. The veneer strips can be pressed in a continuous press to form long beams. Douglas fir and southern yellow pine[1] are the most commonly used wood species. Parallel strand lumber is designed for use in structures with long free spans.

Composite elements (I-beams)

I-beams are composite elements that consist of two flanges and an intermediate web which are glued together. They are intended to be used as load-bearing elements. The top and bottom flanges are made of strength graded structural timber, glulam or LVL. The webs are mainly made of oriented strand board or hardboards. The elements are used as columns, floor and roof beams.

Cross-Laminated Timber (CLT)

CLT consists of at least three layers of wood planks glued together (or joined using dowels), where the direction of the grain in adjacent layers is perpendicular to each other. Individual planks are visually or machine graded. Lay-up of CLT has to be symmetrical in cross section of the product. Planks may be joined by edge-gluing and may also be finger-jointed in the longitudinal direction.

Laminated Veneer Lumber (LVL)

LVL is used as a panel or beam product. It consists of peeled spruce or pine veneers up to 6 mm thick. LVL is manufactured in a continuous process, using a phenolic resin. LVL containing veneers with fibres aligned exclusively in the major axis is used in load-bearing structures, trusses, beams and rafters. LVL can be used in the same applications as glulam.

Figure 3.7. Examples of engineered construction materials
Source: dataholz.eu

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[1] Southern yellow pine is a commercial classification for a group of four pines species – whose wood has similar characteristics – growing in southern United States of America, namely: shortleaf pine, slash pine, longleaf pine and loblolly pine.

Market situation

The two largest producers of sawnwood are also the two largest consumers. China's apparent consumption was 130 million cubic metres in 2019 and the United States of America's was 102 million cubic metres in the same year (FAOSTAT, 2020). China also imports coniferous and non-coniferous sawnwood, mainly from the Russian Federation (11.5 million cubic metres) and Canada (6.8 million cubic metres). The United States of America imports sawnwood mainly from Canada, trading 18.8 million cubic metres of coniferous sawnwood in 2019 (FAOSTAT, 2020).

From 2010 until early 2018, coniferous lumber prices increased slightly from about USD 250 per thousand board feet at the beginning of this period to nearly USD 600 per thousand board feet at the end. After a slight decrease, prices started to increase steadily again, reaching nearly USD 950 per thousand board feet in September 2020, then decreased once more to USD 650 per thousand board feet at the end of 2020 (Investing.com, 2020; NAHB, 2020). One of the reasons for the price increase in the United States of America was the lower lumber stock when construction activities restarted following temporary closure of the mills and businesses due to COVID-19 (Saefong, 2020).

Comprehensive statistics are not yet available for production, trade and apparent consumption of engineered construction materials. However, as indicated elsewhere in this report, by compiling data on known production capacities in the major CLT-producing countries, we get an indicative number of 2.5 million cubic metres of CLT output in the United States of America, European Union and The Russian Federation combined. This seems to be in tune with the estimated global annual CLT production of 3 million cubic metres by 2030 (Espinoza *et al.*, 2016). However, a cautious estimate of the potential wood construction market by Hurmekoski *et al.* (2018), for a volume corresponding to only 0.1 percent of the total global concrete market by mass, suggested required production of up to 40 million cubic metres of wood products. It is therefore expected that CLT and other mass timber products will continue to gain market share over the coming decades. The available information is expected to improve starting 2022 with the entry into force of the updated Harmonized System trade classification, with the addition of commodity codes for various engineered structural timber products (HS441880), including glulam (HS441881), CLT (HS441882), I-beams (HS441883) and other types (HS441884).

Market drivers and forecasts

Due to their perceived environmentally friendliness, acoustics, insulation and other qualities, there is interest in wooden buildings among public and private customers. When promoting high-rise wooden construction, the regulations are updated in many regions to allow for such construction to be more widely implemented. Proponents of the wood industry see great potential for CLT and glulam in enabling wood use in the construction of large and tall structures that previously were the sole domain of steel and concrete (UNECE/FAO, 2019). In 2017, the global CLT market was valued at USD 603 million and projected to reach USD 1.6 billion in 2024 (UNECE/FAO, 2019). Production capacities are rising year-on-year in major markets, primarily in Europe, but also in the United States of America, Japan and the Russian Federation. With high demography, rural exodus and, consequently, high urbanization pressure in Asian and African regions, the strong potential of wood-based construction should be considered there too, especially given that the resource is readily available. Chapter 4.1 provides a more detailed analysis of CLT and LCL specifically with a focused analysis of their substitution potential for fossil fuel based products.

3.4 Cellulosic fibres for textiles

Product definition

Wood pulp has been used for more than a century to manufacture viscose for the textile industry. Viscose, acetate and lyocell are the three major types of regenerated cellulose fibre. Wood pulp is the main cellulose feedstock used to produce regenerated cellulose fibre, but other cellulose products or residues (e.g. bamboo, bast fibres, cotton linters and sugarcane bagasse) are increasingly used as additional cellulose feedstock (Chen, 2015). Cellulose acetate fibre is similar to rayon but uses acetic acid in its production. Global demand for acetate fibre peaked in the early 1970s to later decline as fabric manufacturers moved to less expensive materials such as polyester (Textile Exchange, 2020).

Use of recovered fibre in manufacturing

The market share of recycled cellulosic fibres is still very small, representing less than 1 percent of all man-made cellulosic fibres in 2019 (Textile Exchange, 2020). The cellulosic fibre recycling process is still under development and companies are investing in technologies to use pre- and post-consumer textile fibres as feedstock. Some important advances in the area of cellulosic fibre recycling for textiles are:

- Circulose (by Renewcell, Sweden)
- Infinited Fiber (by Infinited Fiber, Finland)
- Ioncell (by Aalto University, Finland)
- NuCyl (by Evrnu, United States of America)
- Textloop (by Circular System, United States of America)

Many other companies around the world are developing recycling processes to produce textile fibres from cotton and other cellulose-rich feedstocks. While these recycling processes are proving to be technically feasible, it is still easier and more cost-effective to process virgin cellulosic pulp (Şevval Taşar, 2020), which could pose a challenge for the adoption of these textile recycling technologies. Despite this constraint, the textile and fashion industries seem determined to adopt more sustainable practices, with 86 fashion companies signing the 2020 Circular Fashion System Commitment and agreeing to take real action towards a more circular system (Global Fashion Agenda, 2020).

Market situation

The three largest producers of dissolving pulp, which is mainly used to produce viscose, are China (1.8 million tonnes), the United States of America (1.3 million tonnes) and South Africa (nearly 1 million tonnes). When it comes to global apparent consumption of dissolving pulp, China accounts for the largest share (60 percent), followed by India (10 percent), the United States of America and Indonesia (6 percent each) (FAOSTAT, 2020).

The global production volume of all man-made cellulosic fibres combined was about 7 million tonnes in 2019. Production in Europe and the Americas has been fairly stable since the 1990s, but in Asia it has been increasing since the early 2000s (CIRFS, 2018). Viscose is the most important man-made cellulosic fibre, with market share of around 79 percent of all man-made cellulosic fibres, followed by cellulose acetate fibre with around 13 percent (Textile Exchange, 2020). The production volume of viscose was nearly 6 million tonnes in 2019, with compound annual growth rate of viscose fibre estimated at about 6–7 percent (Textile Exchange, 2020) from 2017 to 2022. The production volume of cellulose acetate was around 1 million tonnes in 2019, but its use was mainly for non-textile applications (Textile Exchange, 2020). The proportion of viscose in clothing and textiles produced by leading brands varies between 10 percent and 14 percent in Europe (Statista, 2020), which indicates that synthetics and cotton still account for a large market share.

Market drivers and forecasts

With a bio-geophysical limit to global cotton production – currently, production stands at about 25 million tonnes per year (OECD and FAO, 2020) – as well as consumer-driven demand for natural and environmentally friendly fibres, the production output of wood-based fibre is set to rise rapidly. It is estimated that current global textile production is around 93 million tonnes per year, of which around 53 million tonnes of fibre are produced annually for clothing (Ellen MacArthur Foundation, 2017). The global market for man-made cellulose fibres is estimated at 6.4 million tonnes in 2020 and 8.6 million tonnes by 2027 (ReportLinker, 2020).

The largest share of dissolving pulp is used to produce viscose for the clothing industry. Dissolving pulp production has been increasing steadily since the early 2000s, at a rate of 6.3 percent per year (for the period 2000–2018) (FAOSTAT, 2020; Kallio, 2021). However, this growth rate is likely to slow down in the long run, as it would require large capacity investments by the forest industry (Kallio, 2021).

In many countries, the residues from sawmills are used in the production of low-value products and energy (see Box 3). These residues could be used in the development of industrial developments or integrated biorefineries, where small logs and residues would be used for the production of high value-added products such as bioplastics, biocomposites, biochemicals and wood-based textiles (Hurmekoski *et al*., 2018; Kallio, 2021; Liu *et al*., 2016; Mateos-Espejel, Radiotis and Jemaa, 2013). Some pulp mills have been converted from kraft pulp (for making paper) to dissolving pulp (for making cellulosic materials) (Kumar and Christopher, 2017; Lundberg *et al*., 2014), which can be an advantageous solution, especially if mills have the flexibility to produce paper-grade pulp or textile-grade pulp, depending on the market situation (Kallio, 2021).

3.5 Resin and its chemical derivates

Product definition

Forests can provide many raw materials and products other than wood, such as berries, mushrooms, medicinal plants, nuts, resins and sap (Lovrić *et al*., 2020; see also Box 4: Non-Wood Forest Products (NWFPs)). Tree resins are one type of NWFP and have been used for many centuries in a range of applications, for example as a waterproof substance for coating ropes and tarps, or transformed into tar or pitch to seal wooden ships (Coppen and Hone, 1995). Nowadays, chemical derivates from resin are used to manufacture hundreds of products in the chemical and food industries, as raw material for products such as disinfectants, detergents,

Box 3: Wood for energy

Approximately half of global roundwood removals are used as fuelwood. Africa, Asia, and Central and South America represented 88 percent of apparent global fuelwood consumption over the period 2014–2018 (FAOSTAT, 2020), to a large extent for household cooking use (FAO, 2014). In these largely developing regions of the world, fuelwood production accounted for 50 percent of global total roundwood removals in 1961–1965 and 44 percent in 2014–2018 (FAOSTAT, 2020). Over the period 2014–2018, the share of all roundwood removals in Africa, Asia, and Central and South America used as fuelwood was 90 percent, 65 percent, and 52 percent, respectively (FAOSTAT, 2020). Considering these shares, fuelwood holds particular significance in these regions. Given the importance of fuelwood to people's everyday lives, it is also relevant to several SDGs, including SDG 1 (No poverty), SDG 2 (Zero hunger), and SDG 7 (Affordable and clean energy) (Bull, 2018; FAO, 2018; UNEP, 2019a).

In the aforementioned developing regions of the world, between 16 percent and 63 percent of households used wood as the main fuel for cooking in 2011, and around 11 percent of people used fuelwood to boil and sterilize water (FAO, 2014). Consequently, fuelwood is an important contributor to increased nutrient availability and food safety. As an energy source, it is particularly accessible to the poorer segments of a population (GIZ, 2014). Apart from its importance in subsistence uses, fuelwood collection and production also contributes to household economies and livelihoods with income generated if the wood is sold. For example, some 13 percent of the population in the three regions were engaged at least part-time in the production of fuelwood in 2011 (FAO, 2014).

In Europe and North America, which accounted for 12 percent of apparent global fuelwood consumption between 2014 and 2018 (FAOSTAT, 2020), fuelwood is mainly used for heating and energy generation for industry (Davidsdottir, 2013; WHO, 2015). In the UNECE region, fuelwood consumption was nearly 1 billion cubic metres in 2013 and, according to estimations, the region could be producing 1.8 billion cubic metres of fuelwood by 2030 (UNECE/FAO, 2017). Such an upward projection is supported by policies that aim to promote bioenergy to mitigate climate change.

Fuelwood production and use also come with some notable challenges. Low-technology burning of fuelwood causes air pollution, which results in about 2.5 million deaths per year globally (FAO, 2014). According to a study, 27–34 percent of fuelwood harvested in pan-tropical regions was unsustainable in 2009, with large geographic variations (Bailis *et al.*, 2015). According to the same study, CO_2 emissions from fuelwood corresponded to approximately 2 percent of global emissions. Consequently, there are important issues to be addressed with fuelwood to ensure sustainable harvesting and collection, as well as cleaner and more efficient burning (FAO, 2020).

paints, adhesives and flavourings. Even though there are many tree species that produce resin, most commercial natural resins comes from pine trees. The chemical compounds from these trees are known in the industry as pine chemicals.

There are several methods to extract resin from trees and to produce its chemical derivates (or pine chemicals). The most common extraction method consists in tapping resin (or oleoresin) from standing live trees. The second extraction method involves removing old tree stumps from the ground, pulverizing them, and extracting the chemical compounds with solvents. The resin is usually separated into two intermediate products – a volatile fraction, turpentine, and a solid fraction, rosin (also commonly known as colophony).

Turpentine and colophony can also be produced using a method that derives from the pulping industry. This involves the distillation of crude tall oil – a by-product from the kraft pulping industry – into tall oil rosin, among several other chemicals. The kraft pulping process also yields crude sulphate turpentine as an important by-product. All derivates from pine chemicals can

Box 4: Non-Wood Forest Products (NWFPs)

Besides wood-based products, the world's forests also produce NWFPs such as berries, mushrooms, aromatic and decorative plant material, saps and resins, nuts, honey and game. According to existing statistics for marketed NWFPs (FAO, 2020), these products represented an economic value of USD 7.7 billion in 2015. Most of these NWFPs comprised of edible plants (37 percent), followed by ornamental plants (22 percent), wild meat (9 percent), other plant products (8 percent), honey and beeswax (7 percent), and medicinal and aromatic plants (5 percent) (Figure 3.8).

Data on the collection and consumption of NWFPs are not complete or accurate. Firstly, data on NWFPs are only available for about half of the global forest area (FAO, 2020). Secondly, data on NWFPs fluctuate substantially from year to year. For example, the economic value of NWFPs reported for Europe ranges between USD 1 billion and USD 2.3 billion (FOREST EUROPE, 2015; FOREST EUROPE, UNECE and FAO, 2011; UNECE/FAO, 2000). These fluctuations do not represent trends in the value of NWFPs, but rather trends in the quality of national-level data (FOREST EUROPE, 2015; FOREST EUROPE, UNECE and FAO, 2011). Thirdly, the majority of NWFPs collected do not enter formal markets. Based on a combination of official statistics and key expert interviews, the estimated income from informal collection was USD 88 billion in 2011 (FAO, 2014), three-quarters of which is produced within Asia and Oceania (Figure 3.9). Research-based estimations of the economic value of NWFPs in informal markets are also unreliable and incomplete (Wahlén, 2017), and are strongly affected by the methodology used to collect data (Gram, 2001). However, none of these points considers that the majority of collected NWFPs are not marketed at all; they are more likely used for self-consumption, i.e. consumed within households. A recent study involving over 17,000 households (Lovrić *et al.*, 2020) found that the value of total annual plant-based NWFP removals in Europe is USD 25.5 billion, 86 percent of which is collected for self-consumption (Figure 3.9). This value is equal to 71 percent of annual roundwood removals in Europe (FOREST EUROPE, 2015).

Many NWFPs also have largely untapped upscaling potential for use as chemical substances (e.g. amygdalin from the Rosaceae species in cancer treatment (Becker, Fromm and Mantau, 2015)). Thanks to new technologies, fungi can be used as a substitute for insulation materials for buildings or packaging products, as an alternative to natural leather, and used to digest plastic, pesticides and crude oil (Sheldrake, 2020). Poplar bark can be used as a biopesticide or in cosmetics (Devappa, Rakshit and Dekker, 2015), cork can be used in clothing industry (Wolfslehner, Prokofieva and Mavsar, 2019), and many NWFPs can be a valuable material source of secondary metabolites (Becker, Fromm and Mantau, 2015), and where territorial and ecological marketing is applied, the products can achieve higher value (Wiersum, Wong and Vacik, 2018). The main problems associated with this type of NWFP usage are the relatively high cost of extraction from the forest, legislative hurdles, and problems with keeping their structural and chemical properties constant. A frequent solution to these problems is their (partial) domestication, which has the drawback of decreasing the concentration of the desired chemical compounds and diminishing ecological marketing opportunities (Becker, Fromm and Mantau, 2015).

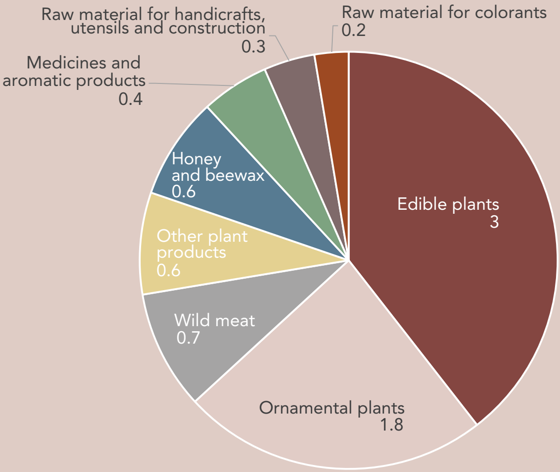

Figure 3.8. Global value (billion USD) of formally marketed NWFPs (in 2015)
Source: FAO (2020)

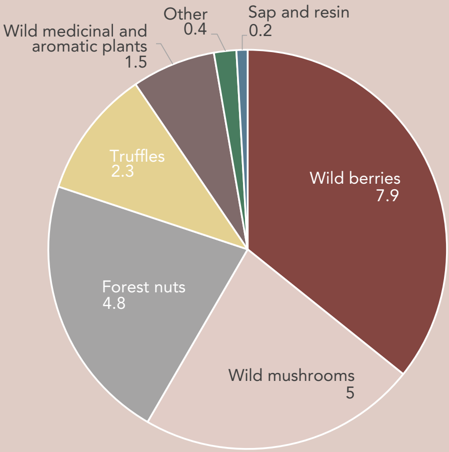

Figure 3.9. Value (billion USD) of European non-marketed plant-based NWFPs (in 2015)
Source: Lovrić *et al.* (2020)

Solely focusing on the value of NWFPs masks many important characteristics of these products. NWFPs are an important source of subsistence (Ambrose-Oji, 2003; Belcher, Ruíz-Pérez and Achdiawan, 2005; Heubach *et al.*, 2011; Kar and Jacobson, 2012; Mahapatra, Albers and Robinson, 2005), especially for low-income households in developing countries, for which they often represent a key income source (Asfaw *et al.*, 2013; Babulo *et al.*, 2009; Qureshi and Kumar, 1998; Wahlén, 2017). They also provide food security, have an important spiritual and cultural role (Pardo-de-Santayana *et al.*, 2007; Seeland and Staniszewski, 2007; Shackleton and Pandey, 2014), are closely linked to the recreational function of the forests (de Aragón *et al.*, 2011; Kangas and Markkanen, 2001; Sievänen, Pouta and Neuvonen, 2005) and are a crucial part of traditional medicine, which is used by 2.8 billion people around the world (WHO, 2002). All the figures above focus on NWFPs produced in forests. If we included NWFPs that partially come from agricultural production, all the figures stated above would at least double (e.g. Pettenella *et al.* (2014).

be further broken down into a large array of chemicals which form raw materials for several industries. A simplified diagram with pathways to produce pine chemicals is presented in Figure 3.10.

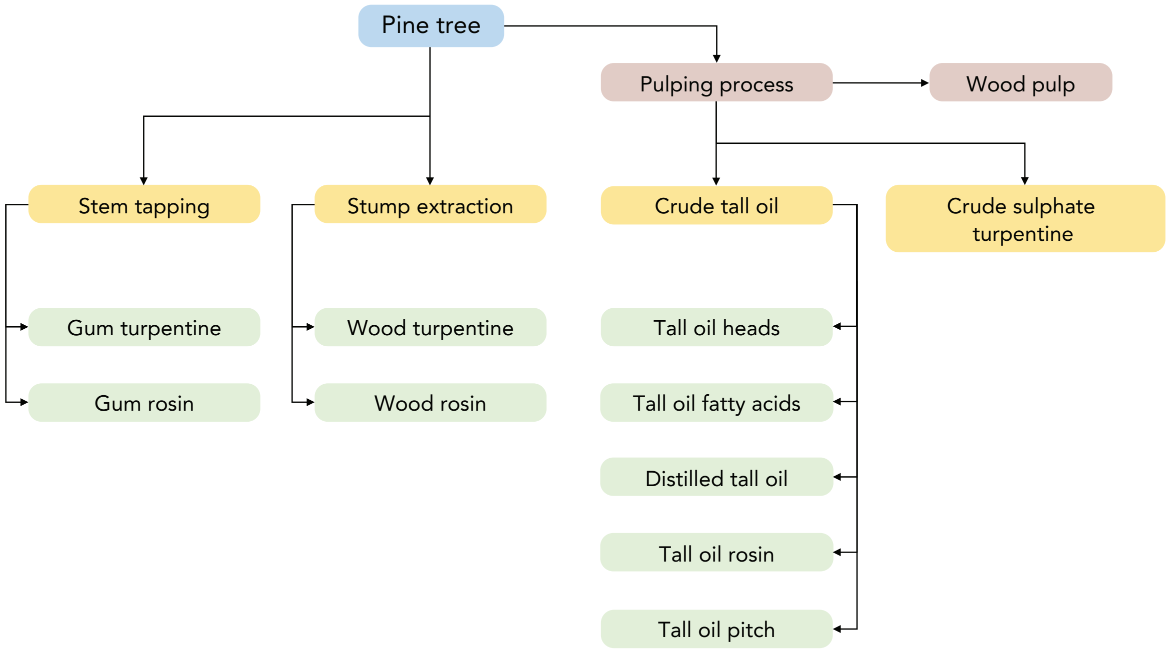

Figure 3.10. Simplified pine chemical product pathways

Source: Adapted from AAC (2011) and Fraunhofer Institute (2016)

The chemical composition of turpentine varies according to tree species and age. It is commonly used in the pharmaceutical industry or in the chemical industry as a solvent for paints, or to produce fragrances, cleaning products, essential oils, etc. Rosin is used in the production of inks and paints, adhesives, pharmaceuticals, chewing gums, etc. Because turpentine and rosin are the most common pine chemicals, they will be the focus of this review.

Market situation

Resin: production and trade

The global production of forest-based resins is about 1.4 million tonnes (in 2019) (Baumassy, 2019). Currently, the largest producer in the world is China, followed by Brazil and Indonesia. These three countries together produce more than 90 percent of the resin in the world. However, resin production in China has been declining because of the low productivity of the methods used and increases in wages (Clopeau and Orazio, 2019).

The productivity in terms of volume of resin extracted is higher in Brazil than in other countries. In 2017–2018, Brazil produced 185.7 thousand tonnes of resin (ARESB, 2018). Due to a combination of species selection, climate conditions and the production method, pine trees planted in the country can produce an average 3 kilograms of resin per year, for about 15 years. Due to forest resources and labour availability, together with a high production yield, Brazil still has the potential to increase production. On average, Brazil produces an annual 4 180 kilograms per hectare, while Argentina produces an annual 3 960 kilograms per hectare and France an annual 896 kilograms per hectare (Clopeau and Orazio, 2019). All other countries produce less than 800 kilograms per hectare annually. The duration of the production season is also longer in Brazil, lasting 10 months per year, while in Indonesia it lasts nine months, in Spain over eight months, and in China six months. Regarding overall production costs, Indonesia has the lowest costs, followed by Brazil and Argentina (Clopeau and Orazio, 2019). In Indonesia, productivity per hectare is low due to the low efficiency of the extraction process and low yield per tree. This downside is, at least in part, compensated by low labour costs.

Resin production in China has been declining due to the increase in labour costs and pressure to preserve forest resources in the country. This, associated with an increase in resin consumption, has led to a decline in resin export volumes since 2006 (Clopeau and Orazio, 2019). As a result, China, once self-sufficient in forest-based resin, has become an importer (Clopeau and Orazio, 2019). One of the suppliers of resin to China is Brazil. In 2018, this country exported nearly 27 000 tonnes of pine resin (COMEX, 2020). About 9 percent of this volume was exported to China, 12 percent to Vietnam, 70 percent to Portugal, and 9 percent to other countries (COMEX, 2020).

Turpentine: production and trade

Most of the turpentine produced in the world comes from the pulping process (as crude sulphate turpentine) and from stem tapping, while the volume of wood turpentine produced annually is minimal. Global production of gum turpentine is about 140 000 tonnes (Baumassy, 2019). The three largest turpentine producers are China, Brazil, and Indonesia (Figure 3.9). Meanwhile, global annual production of crude sulphate turpentine is around 205 thousand tonnes, with most of the volumes produced in North America, followed by Europe and The Russian Federation combined (Baumassy, 2019) (Figure 3.11).

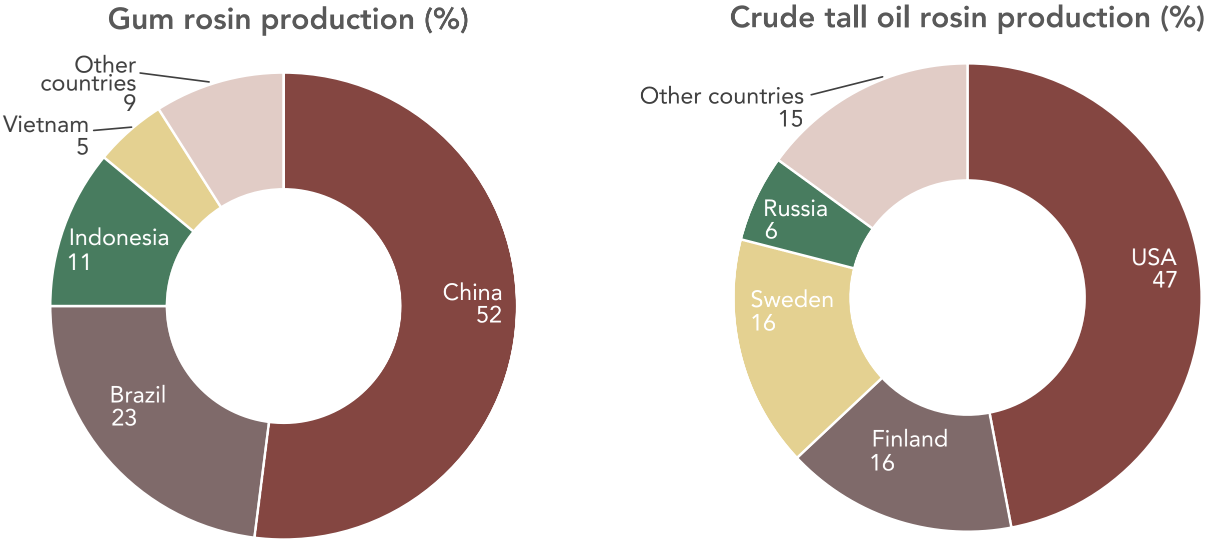

Figure 3.11. Main turpentine producing countries
Source: Adapted from Baumassy (2019)

Total turpentine exports were valued at USD 202 million in 2014, which represents 7 percent of all pine chemicals traded that year (Bhatia, 2016).

Rosin: production and trade

The global rosin market represents 73 percent of the pine chemicals traded in 2014 (Bhatia, 2016). The global production of rosin is around 1.3 million tonnes (Baumassy, 2019). Gum rosin accounts for 63 percent of the supply, while rosin from crude tall oil is about 36 percent and wood rosin 1 percent (Baumassy, 2019). The largest producer of gum rosin is China, followed by Brazil and Indonesia (Figure 3.10). When it comes to the production of rosin from crude tall oil, the countries that have strong pulp and paper industries are also the largest producers of rosin from crude tall oil, namely the United States of America – the largest producer, then Finland and Sweden who share second place (Figure 3.12).

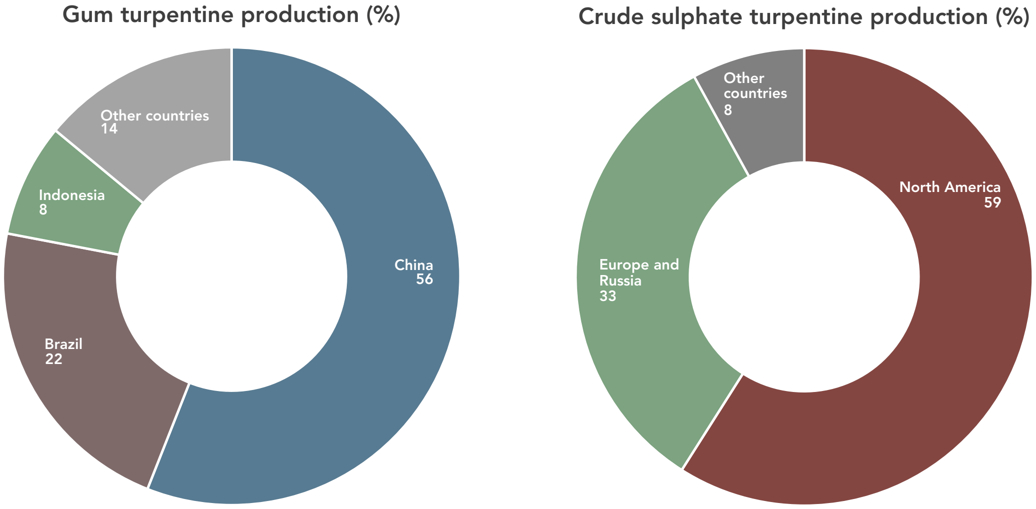

Figure 3.12. Main (gum and crude tall oil) rosin producing countries
Source: Adapted from Baumassy (2019)

Total rosin exports were valued at USD 2 billion in 2014 (Bhatia, 2016). The largest exporter is China (48 percent), followed by Indonesia (18 percent), Brazil (16 percent), Finland (12 percent) and Belgium (6 percent) (Baumassy, 2019). The three major importers of rosin were Japan, the Netherlands and Portugal (in 2015) (Clopeau and Orazio, 2019). Rosin consumption in Europe alone over the same period was around 325 000 tonnes, from both domestic and foreign sources (Fraunhofer Institute, 2016). Even though China remains the largest exporter of rosin, because of a decline in production of resin and its derivates, the country now imports around 12 percent of the rosin consumed (in 2017) (Clopeau and Orazio, 2019).

Market drivers and forecasts

The pine chemicals market has always fluctuated and is still dependent on the price of their fossil-based counterparts. The replacement of gum rosin with hydrocarbon resin – a petroleum derivate – has been observed since 2015, following a decrease in oil prices (Clopeau and Orazio, 2019). Despite this, the global pine chemicals market continues to grow and is valued at USD 5 billion (in 2019) (Baumassy, 2019). In Europe, for instance, tree resin production, which almost came to a halt in the 1990s, is currently growing, especially in the Mediterranean.

Demand for crude tall oil is increasing – especially for biofuels – and fractionation of this raw material is still at 80 percent of its current world capacity (Baumassy, 2019). Despite interest from industry and the possibility of increasing fractionation, crude tall oil production is (and has historically been) limited by resource availability (Fraunhofer Institute, 2016). The surfactants industry is driven by worldwide concerns over the biodegradeability and toxicity of fossil-based chemical compounds (Rebello et al., 2014) and presents an interesting avenue for producing biosurfactants from pine chemicals.

3.6 Summary

The recycling and cascading use of graphic paper, which were occurring long before circular bioeconomy discourses emerged, are a prime example of a circular bioeconomy and could potentially provide lessons for the eco-design and collection systems of other forest products supporting a circular bioeconomy. However, little is still known about the environmental impacts of substituting internet and electronic media consumption for graphic paper. While graphic paper consumption is globally decreasing, the market trend is the opposite for traditional wrapping and packaging, as the consumption of this product category increases due to trends such as e-commerce. The wrapping and packaging market segment as a whole is growing, yet plastic and wood-based packaging have specific applications, which do not always allow substitution.

Wood-based construction is still dominated by more traditional products such as sawnwood and panels, particularly in the market segment for low-rise building construction. However, production and consumption of engineered construction materials are rising, mainly due to increased application in wood-frame multistorey construction, where glulam and CLT can substitute steel and concrete. CLT can be used in many construction applications, including floors, walls and roofs. It can substitute several GHG-intensive construction materials, such as reinforced concrete (Brandner *et al.*, 2016), steel and masonry. A recent study estimated that the construction of mid-rise urban buildings using engineered wood products could prevent emissions of 5 million tonnes to 1 196 million tonnes CO_2 per year until 2050 (excluding carbon storage effects), depending on floor space per capita, the amount of wood used in construction and how fast countries adopt new building practices (Churkina *et al.*, 2020). D'Amico, Pomponi and Hart (2021) estimated that using CLT as floor slabs in buildings could provide a global GHG emission reduction potential of 20 million tonnes to 80 million tonnes CO_2e (95 percent confidence interval) by 2050 with an average of around 50 million tonnes CO_2e (not including the carbon sequestration potential in the timber itself).

According to current information, pine chemicals appear to have a smaller carbon footprint than their fossil-based equivalents (Cashman, Moran and Gaglione, 2016). Growing environmental concerns regarding the use of fossil-based products, such as hydrocarbon resins, allied with increased production of tree resin and crude tall oil derivates, could favour the substitution, at least partially, of fossil-based for bio-based chemical compounds. This market shows an annual growth rate of 3.5 percent, currently estimated at 2.6 million tonnes (Fraunhofer Institute, 2016). When it comes to pine chemical production, there is still a lot of untapped potential.

Take-home messages

- For some forest product groups, significant changes have occurred in recent years in product development and/or because of structural changes driven by information technology and e-commerce. Graphic paper is one product group marked by structural change, where demand has stabilized and is declining in some world regions, linked with the adoption of internet and electronic media.
- Paper recycling presents a prime example for a functioning circular bioeconomy and provides insights for the eco-design and collection systems for other forest products, especially in cases where wastepaper is utilized domestically and not traded globally.
- The growing interest in engineered wood products is linked to increased application in wood-frame multistorey construction, due to their perceived environmental friendliness, acoustics, insulation, and other qualities.
- Based on current information, chemicals derived from resin have a smaller carbon footprint than their fossil-based equivalents, which could favour the substitution, at least partially, of fossil-based chemicals.

4 Emerging wood-based products with innovation potential for substitution

The development of products that could be potentially substituted for fossil-based or GHG-intensive materials is one element of the circular bioeconomy. The forest sector has been actively trying to find alternative products that are not simply technical substitutes for traditional materials, but that also help solve some of the problems related to increases in GHG emissions, depletion of natural resources, and generation of residues and waste.

There is a large assortment of innovative forest products at different stages of development, such as lignin-based adhesives for wood panels, a lignin-based anode material (to substitute fossil-based graphite, used in rechargeable batteries), wood-based composites for injection moulding and 3D printing (for furniture and reusable casting moulds), and nanocellulose-based filters for microplastics, to name a few (Mäntyranta, 2020b, 2020c; VTT, 2020). There are thus many products under development or production and this chapter presents some of the novel and emerging forest products that could displace fossil-based and GHG-intensive products in the near future. The focus is on innovative products that have the potential to increase their market share or to enter the market in the next 5–10 years. We have not covered new products at the early stages of development and that will not contribute to the bioeconomy any time soon. A description of the methodology used to select the products is available in Appendix 1. Table 4.1 presents the selected products, as well as their most common uses and possible applications.

Table 4.1. Selected innovative forest-based products and their main uses and applications

Product	Main uses and applications
Engineered wood products (CLT, LVL)	Building elements
Wood foam	Insulation (thermal and acoustic), packaging
Bioplastics	Packaging
Wood-based composites	Packaging, disposable products
Wood-based textile fibres	Textiles

4.1 Engineered wood products

In the past decade or so, wood constructions have been transforming the skyline of many cities across the globe. Recent advances in wood construction technologies are making it possible to build high-rise constructions over 50 metres tall (or 14 storeys) (Tollefson, 2017). In the mid-2010s, buildings over six storeys high were built in Sweden, Canada, the United States of America, the United Kingdom of Great Britain and Northern Ireland and Norway (Green and Taggart, 2017) using CLT and LVL panels, among other wood-based products such as glulam and parallel strand lumber. Engineered wood products are thought to provide opportunities for climate change mitigation as carbon is stored for a long period and because wood-based products may substitute for other non-renewable and more GHG-intensive materials (e.g. Amiri *et al.*, 2020; Churkina *et al.*, 2020; D'Amico, Pomponi and Hart, 2021).

Building codes are being revised to allow for or to facilitate the use of engineered wood products in structural applications. For example, in 2016, Australia's National Construction Code was amended, allowing the construction of buildings up to 25 metres high using wood products. In 2019, the International Code Council, a non-profit association that develops model codes and standards for construction used worldwide, approved 14 code changes proposed for tall mass timber, defining fire safety requirements, allowable heights, and the number of storeys for tall mass timber buildings of up to 18 storeys (Mass Timber Code Coalition, 2019). In many countries, building codes and regulations must yet be revised to allow for the use of CLT as a structural element in high-rise constructions. In the meantime, CLT will most likely be used in low- and mid-rise constructions.

4.1.1 Cross-Laminated Timber (CLT)

Product description and required feedstock

CLT is a solid wood panel with variable final dimensions and made according to its intended use. It is usually composed of an odd number of layers (from three to seven), each made of sawnwood or structural composite lumber, placed side-by-side, arranged crosswise to each other at a 90° angle and glued together on their wide faces, although sometimes on the narrow faces (Figure 4.1) (Brandner *et al.*, 2016). Structural composite lumber includes LVL, laminated strand lumber, oriented strand lumber, and parallel strand lumber (Karacabeyli and Gagnon, 2019). CLT thickness usually varies between 1.5 cm and 5 cm, and its width between 6 cm and 24 cm. Custom dimensions are possible for CLT panels, with restrictions defined by transportation (Think Wood, 2020).

Figure 4.1. Cross-laminated timber (CLT) panels

Source: Crosslam

CLT panels are strong yet light compared to the materials traditionally used in construction (e.g. concrete or steel). Because of its high load-bearing capacity, CLT can be used in several structural applications, as well as ceilings, floors and walls (Anttonen, 2015). Some of the advantages of building with CLT are the fast construction and assembly time, low overall weight, adequate resistance, and flexibility for earthquake-prone areas (Anttonen, 2015), as well as good thermal and fire performance. The fact that CLT allows for a lighter construction helps reduce the cost and complexity of foundations and footings (UNECE/FAO, 2015). The general production process of CLT involves the visual and mechanical grading of the sawnwood, planing and cutting the sorted lumber pieces, applying adhesive, laying up the lumber side-by-side and stacking the layers at a 90° angle, pressing, and cutting to size (Figure 4.2).

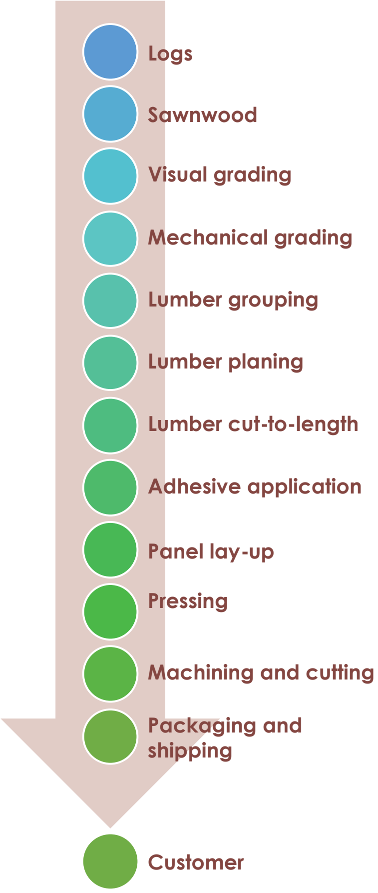

Figure 4.2. CLT production process

The type of adhesive typically used is formaldehyde-free polyurethane, but other adhesives (e.g. phenol-resorcinol formaldehyde and emulsion polymer isocyanate) can be used according to the wood species and other technical requirements. Adhesives are an important factor that influences the environmental performance of engineered wood products, especially when it comes to the sourcing of raw materials, emissions of volatile organic compounds during the use stage, and disposal at the end of the life cycle (Messmer, 2015). For this, bio-based adhesives have been considered as a possible solution for substituting certain synthetic adhesives. While using lignin-based adhesives in engineered wood panels is not yet cost-effective, substituting part of the synthetic phenol with industrial lignin in the adhesive composition is technically feasible, with good results (Hemmilä *et al.*, 2017; Nakos *et al.*, 2016). Some companies avoid using adhesives, opting for nails or wooden dowels to join the wood boards (Muszynski *et al.*, 2020).

The maximum dimensions are 3 m in width and 12 m in length, frequently restricted by transportation regulations (Karacabeyli and Gagnon, 2019). CLT is usually produced using softwoods such as spruce, pine, larch, and fir. However, some companies may also produce the panels with other species, such as eucalypt and bamboo.

In 2015, the first European standard on CLT was published (EN 16351:2015), specifying the product requirements. Japan, a country with a high incidence of earthquakes, produced a

CLT product standard in 2013 and had building law that allows the use of CLT in buildings approved in 2016. In North America, the ANSI/APA PRG 320 standard was published in 2011.

Current global demand and production

Currently, there are 60 registered CLT production lines across the world (Jauk, 2019b). The global production of CLT was around 625 000 cubic metres in 2014 (UNECE/FAO, 2015) and is expected to reach 2.0–2.5 million cubic metres by the end of 2020 (Muszynski *et al.*, 2020). Most of the global production (70 percent) comes currently from Germany, Austria and Switzerland, and 14 percent from the rest of the European Union (notably Italy and France), 12 percent from North America, and 4 percent from the rest of the world (Muszynski *et al.*, 2020). According to estimates, Europe currently produces around 1.8 million cubic metres per year of CLT (UNECE/FAO, 2018). The CLT industry in Europe, especially in Germany, Austria and Switzerland, is very much focused on exports to other European countries and overseas markets (UNECE/FAO, 2015). The market has been increasing largely due to the boost from the construction of multistorey wood buildings across the globe.

Even though Europe is the largest manufacturer of CLT, other countries and regions are investing in the construction of CLT plants. In North America, production is rising slowly but steadily and there is growing interest in the development of the CLT industry from the governments, the forest industry, and other parties including researchers, architects and civil engineers. In the United States of America, the estimated market potential for CLT is thought to be between 2.1 million and 6.4 million cubic metres per year (Karacabeyli and Gagnon, 2013). In Canada, the total production capacity in 2015 was estimated at 110 000 cubic metres (Espinoza *et al.*, 2016). Although in Europe most CLT consumption is for floors, roofs and walls, in North America 65–70 percent of CLT volumes are absorbed by distinctive market segments with industrial applications such as access mats and crane rig mats (Plyvisions, 2019).

The Russian Federation is also investing in the production of engineered wood construction materials. At least two plants are planned to start producing engineered wood products in 2020 (Jauk, 2019b). One of the facilities will produce CLT, with as estimated production capacity of 250 000 cubic metres per year (Woodbizforum, 2019). At least part of the engineered wood construction materials produced in the Russian Federation will remain in the country, as the industry is interested in building high-rise residential buildings of 10 to 25 storeys (Woodbizforum, 2019). In Moscow, there are plans for the construction of a multistorey wood complex using CLT panels produced in the country (Segezha Group, 2018).

In Japan, the first CLT plant started producing in 2011 and by 2014 the country was producing 10 000 cubic metres per year. Current production volume is around 30 000 cubic metres and, according to the CLT roadmap set by the Japanese government, the production should increase to 500 000 cubic metres by 2024 (Muszynski *et al.*, 2017; Passarelli and Koshihara, 2018; Woodbizforum, 2014).

New Zealand's first production line started its commercial operations in 2012 (Muszynski *et al.*, 2017). However, in 2019, the only CLT producer brought its production to a halt due to low profitability of the operations (Jauk, 2019a). Since then, New Zealand has been importing CLT from Australia's sole producer, which started operating in 2015.

Fossil-based or GHG-intensive products that CLT can potentially displace

CLT can substitute precast concrete panels, with the technical advantages of being easier to work with and easier to erect than concrete. Being a wood-based product, CLT can contribute to lowering the GHG emissions of the overall construction. Buildings constructed with wood-based materials emit 20–50 percent net less GHG over a 100-year period than comparable constructions built with steel or concrete building systems (Upton *et al.*, 2008). Simulations with buildings where CLT substituted for traditional construction materials (e.g. steel, concrete, and bricks) have proven to consume 12 percent to 23 percent less energy, according to a study done in China (Dong *et al.*, 2019). However, the buildings that used CLT consumed more energy during the summer because of the cooling system, which indicates that, at least for China, the best use of this type of construction system would be in colder regions.

Knowledge and gaps regarding the environmental impact of CLT

The distance between lumber suppliers and CLT manufacturing facilities and the wood species used are two important factors contributing to environmental impacts during CLT production (Chen, Pierobon and Ganguly, 2019). The type of adhesive used in the panels accounts for only a fraction of the environmental performance of CLT (Messmer, 2015).

Regarding the impact on buildings, CLT panels are lighter than concrete and masonry, permitting smaller building foundations (Karacabeyli and Gagnon, 2019). CLT buildings emit less GHG during their life cycle and have an overall smaller environmental impact than similar concrete-steel buildings (Durlinger, Crossin and Wong, 2013). Depending on the construction system, CLT can help lower the energy costs of buildings. In general, at the end-of-life stage, CLT can be mechanically recycled or used as a source of energy, and the wood portion is biodegradable.

Policies and incentives that have enabled the increase in use of CLT

The increase in the production and demand for CLT is due, at least in part, to changes in building codes (e.g. Japan's Building Standards Act of 2000, Australia's National Construction Code of 2016, and the International Code Council of 2019) to permit the construction of high-rise buildings using engineered wood as structural and non-structural elements. In addition, several countries have implemented Wood Encouragement Policies and other incentives to improve sustainability in the construction sector (FAO-ACSFI, 2020) by promoting the use of wood products in new buildings. Most high-rise wood buildings are at least partially funded by local, regional or country governments to help architects and engineers develop these challenging projects that would be otherwise too risky for testing and, consequently, for investment.

Some countries have put in place programmes to stimulate use of CLT. A few examples of incentives come from Canada, Japan, France and Finland. The Tall Wood Building Demonstration Initiative and the Green Construction through Wood (GCWood) Program, both from the Canadian government, have given support to the construction of the tallest wood buildings in the country (The Origine in Quebec City, the Brock Commons Tallwood House in Vancouver, and The Arbour in Toronto, with construction set to start in 2021), all using CLT as one of the wood-based materials. The Japanese government's Act on Promotion of the Utilization of Wood in Public Buildings promotes the construction of many public buildings using CLT elements (Passarelli and Koshihara, 2018), including the Park Wood Takamori, the country's first high-rise building that uses CLT. Japan has also been promoting other initiatives focused on improving consumers' perception of wood, including the "Kizukai Undo" and "Mokuiku" (Government of Japan, 2017). The French government will require that all new public buildings must be made from at least 50 percent wood products or other sustainable materials from 2022 (Errard, 2020). This will most likely increase the use of CLT in the construction of buildings in the country, following the example of Hyperion Tower, France's first tall timber building in Bordeaux. In Finland, the Wood Building Programme was created to promote carbon storage in timber structures and support the responsible use of forest resources, among other objectives. This programme has enabled the construction of several wood buildings, such as the Lighthouse, with many other projects under way or in planning stages (Ministry of the Environment, 2020).

Relevant research and innovation initiatives related to CLT

Research and innovation efforts regarding CLT relate to the substitution of traditional synthetic adhesives with bio-based alternatives (e.g. derivates of lignin, tannins or starch) or wooden dowels (Hemmilä *et al.*, 2017; Muszynski *et al.*, 2020; Nakos *et al.*, 2016) to reduce the use of non-renewable materials or avoid the use of components that emit volatile organic compounds during manufacture and use of the product.

4.1.2 Laminated Veneer Lumber (LVL)

Product description and required feedstock

LVL is an advanced wood product made of thin (3 mm-thick) wood veneers that are glued together to form panels, planks, studs or beams (Anttonen, 2015) (Figure 4.3). In North America, either coniferous or deciduous species are used to produce LVL, the most common being pine species, Douglas fir, western hemlock, yellow poplar, and red maple. In Australia, pine or eucalypt are used. In Japan, there is a preference for conifers, with larch and sugi the most frequently used (Finnish Woodworking Industries, 2019).

Due to the advancements in lamination and post-treatment technology, wood defects can be removed, forming a product that is stronger, straighter, more uniform and with a longer span than sawn timber (Plyvisions, 2019). LVL is also less prone to shrinkage and swelling, and less likely to warp, twist or bow than traditional timber (Plyvisions, 2019). Another advantage is its lower thermal conductivity compared to bricks and concrete, combined with long span capability (Plyvisions, 2019).

Figure 4.3. LVL used in the interior of One Main office (project by DECOi Architects) and a close-up of an LVL beam

LVL can be used in several load-bearing or non-load-bearing applications, such as joists, trusses, frames, walls, roofs, and floors (Anttonen, 2015). It is one of the strongest wood-based construction materials relative to its weight, being a well-suited solution when strength, dimensional stability and high load-bearing capacity are essential. It is also becoming a more popular product in construction because it allows for longer spans in structures.

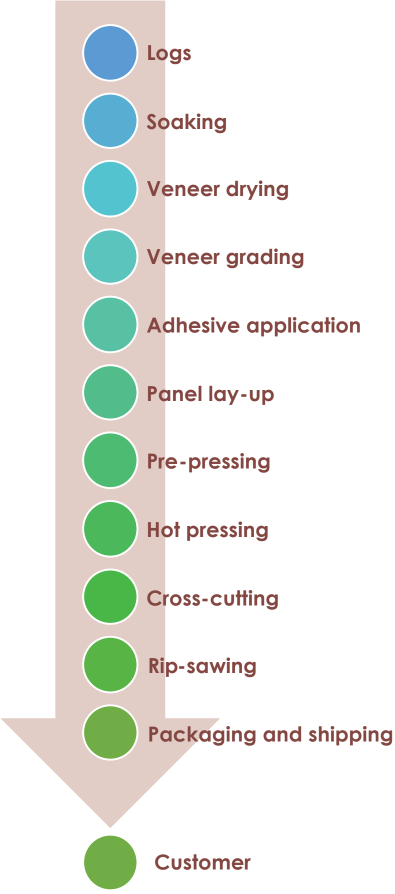

Figure 4.4. LVL production process

The production process involves peeling logs to 3 mm-thick veneers, drying, grading (based on strength and visual quality) and gluing the veneers (in the parallel direction). The veneers are laid up, forming a large 1.8 m or 2.5 m-wide block (or billet). The wood grain in each veneer is oriented along the longitudinal axis of the LVL element, mimicking the structure of a solid piece of lumber (Ochshorn, 2010). Then, the billet is pressed with heat and cut to size (Figure 4.4).

The adhesive is weather-resistant, dark-brown phenol-formaldehyde. In scarf-joints of surface veneers, colourless melamine is used as adhesive for appearance. Even though LVL fulfils the formaldehyde emission requirements, in general the use of phenol-formaldehyde in the adhesive's composition can lower the product's environmental performance (Messmer, 2015). As is the case for CLT, using bio-based adhesives in LVL production could improve the environmental aspects of the product (Hemmilä *et al.*, 2017; Nakos *et al.*, 2016), especially regarding volatile organic compound emissions.

Current global demand and production

The North American production of LVL peaked at 2.6 million cubic metres in 2005, following the growth in residential construction (UNECE/FAO, 2018). Since the 2008 crisis, demand and, consequently, production have been growing steadily. In 2018, production was estimated at 2.3 million cubic metres (APA, 2016).

The growing trend toward the use of engineered wood products in construction is increasing interest in LVL. Demand in Europe is expected to continue to rise at a projected average annual growth rate of 6 percent. Estimated demand for 2020 is more than 440 000 cubic metres (Plyvisions, 2019). The largest markets for LVL in Europe are the Nordic countries and the United Kingdom of Great Britain and Northern Ireland, which together account for 54 percent of the demand in Europe. Other important markets include Germany, Austria, Switzerland, Poland, France, Belgium, the Netherlands and Luxembourg (Plyvisions, 2019).

Fossil-based or GHG-intensive products that LVL can potentially displace

LVL can substitute GHG-intensive products such as cement and steel. Buildings that use LVL as a structural material emit less GHG than an equivalent structure built with concrete and steel. In Norway, a comparison between two buildings with the same foundation, but one constructed with steel and concrete and the other using LVL, showed that the wood-based structure had 35 percent less GHG emissions (Tellnes *et al.*, 2013). Substituting concrete, steel and bricks with durable wood products, such as LVL, also contributes to reducing carbon emissions through storage (Churkina *et al.*, 2020; D’Amico, Pomponi and Hart, 2021).

Knowledge and gaps regarding the environmental impact of LVL

A large share of renewable energy is used to produce LVL, which reduces the GHG emissions from fossil fuels (Puettmann and Wilson, 2005). In addition, as with any wood-based product, the CO2 removed from the atmosphere during tree growth is stored in the product until the end of its life cycle (Finnish Woodworking Industries, 2019). The amount of carbon stored in long-lasting products such as LVL is greater than the emissions caused during the production stage (Puettmann *et al.*, 2010). At the end-of-life stage, LVL products can be reused or recycled, composted (after being reduced to chips) or burned for energy (Finnish Woodworking Industries, 2019).

Policies and incentives that enable the increase in use of LVL

Demand for LVL is slightly increasing due, in part, to changes in building codes, which are stimulating the use of engineered wood products in construction. With LVL becoming a more popular construction material, the European LVL industry has introduced strength classes in construction standards. Modifications will be made to standard EN 14374, which stipulates the requirements for LVL used for structural applications, to define the strength classes necessary for design. Other standards that define general specifications for LVL include ISO 18776:2008 and AS/NZS 4357.X. Standardization is an important step in the development and improvement of a product because it allows the product to enter the market and be fully adopted by customers.

As previously mentioned for CLT, several countries are putting action plans and programmes in place to incentivize the use of wood products in construction. These policies are developed to help reduce GHG emissions, reduce the environmental impacts of construction materials, and promote the local wood economy and culture (UNECE and FAO, 2016). In Finland, for instance, more than a third of GHG emissions are associated with building construction and use. As such, the Finnish government has introduced a Housing Policy which, associated with the Wood Building Programme, stimulates the use of LVL in construction, as observed in the Lighthouse, in Joensuu (Ikonen and Molainen, 2019). Germany's Charter for Wood 2.0 also aims to increase the use of wood products to help mitigate climate change and add value to forest resources while using them more efficiently. The country aims to stimulate the use of wood products, as 90 percent of all mineral resources are used as a raw material to manufacture construction materials. These two examples indicate that government policies and incentives aiming to reduce GHG emissions may contribute to the wider adoption of LVL in constructions.

Relevant research and innovation initiatives related to LVL

Innovation regarding LVL relates to its use in mass timber constructions. Several individual LVL elements can be joined to form continuous columns and beams. Regarding innovations at product level, as for other engineered wood products, synthetic adhesives can be substituted with bio-based alternatives to reduce the use of non-renewable materials and reduce volatile organic compound emissions during manufacture and use of the product (Hemmilä *et al.*, 2017; Nakos *et al.*, 2016). Lignin-based adhesives have already been successfully used on LVL, contributing to an increase in the bio-based input in this product (Mäntyranta, 2020b).

4.2 Wood foam

Product description and required feedstock

Wood foam is a lightweight, cellulose-based rigid foam with sponge-like pores that has low bulk density and high insulating properties (Figure 4.5). It can be produced in several densities, depending on use. Wood foam tiles can be used as acoustic or thermal insulation material in walls or as a middle layer in sandwich boards for furniture and doors. They can also be used in packaging or in products that required energy or liquid absorption. Wood foam tiles can be sawn, glued and drilled, and produce little dust. Wood foam can be combined with metal sheets to form a composite panel, which improves fire resistance properties.

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Figure 4.5. Wood foam tiles and wood foam for packaging

The only component used in the production of wood foam is wood fibre, either from softwoods or hardwoods. It can be produced from woody residues from forest operations, small logs, non-commercial trees, and even cellulose-rich agricultural waste. No binders or resins are used in the production of wood foam; thus, it does not contain toxic or harmful substances.

Because wood foam is not yet produced commercially, the foam mat production process is still at a laboratory scale. During the production process, wood chips are reduced to fibres through thermo-mechanical pulping, a method traditionally used in the pulp and paper industry. Water is added to create a fibre suspension and the foam is created by adding protein that acts as foaming agent. Hydrogen peroxide is added to activate the binding forces of the wood fibres and air is pumped in to increase the pore size. The foam suspension is dried by convection at 130 °C for 30 minutes, and kept overnight at 70 °C. In a commercial production process, the wood foam mats would then be cooled and cut to size (Figure 4.6).

Figure 4.6. Wood foam board production process

Depending on use, wood foam can be produced in the form of tiles or panels, with densities that can vary from 40 kg/m^3 to 280 kg/m^3 (Fraunhofer Institute, 2020). The strength of the final product is determined by the foam density, where the lower the density, the less strong the tile or panel. Much like for paper, fibre length also influences wood foam's mechanical properties. Tiles produced with longer fibres (e.g. pine) have higher tensile strengths compared to tiles produced with shorter fibres (e.g. beech) (Ritter, undated).

As mentioned, wood foam panels could be used for thermal and acoustic insulation, due to their adequate insulating properties. Low-density wood foam panels have thermal conductivity similar to wood fibre insulation boards (around 0.04 W/m·K) and slightly higher than polystyrene (0.03 W/m·K) (Fraunhofer Institute, 2020). Therefore, wood foam could be a feasible substitute for these materials. Regarding acoustic insulation properties, a 30 mm-thick medium-density (70 kg/m^3) beech wood foam tile has sound absorption equivalent to an 80 mm polystyrene tile (Ritter, undated).

When it comes into contact with water, wood foam remains dimensionally stable, swelling less than 1 percent when placed in cold water for 24 hours. However, because it is made of cellulose, it is a hydrophilic material. As expected, water absorption capacity does not depend on the wood foam density (or size of pores), but on the type of feedstock used. During tests, pine foam absorbed less water than foam produced with beech. The fact that wood foam is hydrophilic could be detrimental if this product is used in an environment prone to fungi growth. Therefore, it may be necessary to foresee additional processing of the final product.

Wood foam composite materials

Wood foam can also be used with other materials to combine and improve certain properties. A wood-metal composite material called HoMe foam (from German "Holz-Metall") combines the two materials to improve the flexural strength of wood foam (Ritter, 2019a). The reinforcement of wood foam with a metal skeleton results in a lightweight material suitable for sandwich constructions or for use in stiffening and acoustically insulating components (Ritter, 2019a).

Another possibility is to combine wood foam and textile-reinforced concrete to produce a low-weight element (Ritter, 2019b). While concrete is considered a GHG-intensive material, reducing the volume of this material in buildings by adding wood foam could help reduce the overall CO_2 emissions of the construction project. This wood foam-concrete product has similar technical characteristics to commercial sandwich construction elements (Ritter, 2019b). The advantage of this new product is that it uses wood foam instead of polyurethane or extruded polystyrene – both fossil-based materials – used in the traditional products.

Current global demand and production

Wood foam is not yet produced commercially, but it could become a replacement for certain types of polystyrene (e.g. expanded polystyrene and polystyrene foams). The global production capacity of polystyrene in 2018 was estimated at around 15.5 million tonnes and is expected to increase slightly to about 15.6 million tonnes, by 2023 (Statista, 2019). However, production volume is around 71 percent of production capacity (HDIN Research, 2019), which means that production volume in 2018 was around 11.0 million tonnes. Regarding expanded polystyrene specifically, its global market was estimated at 8.0 million tonnes in 2018 and projected to reach 10.9 million tonnes by 2023 (Markets and Markets, 2018). Most of this growth is attributed to the construction industry, the largest consumer of this type of material.

Fossil-based or GHG-intensive products that wood foam can potentially displace

Moulded wood foam can replace expanded polystyrene in packaging material. Wood foam tiles can substitute expanded polystyrene boards in construction, for acoustic or thermal insulation in walls, or as a middle layer in doors and furniture. Other insulation materials that can be potentially displaced are polyurethane and polyisocyanurate foam boards. For insulation purposes, polyurethane and polyisocyanurate are typically more expensive than polystyrene, but are also more efficient (Pavel and Blagoeva, 2018). Taking all types of thermal insulation materials into consideration, including glass wool, stone wool and the aforementioned foam boards, expanded polystyrene is the most popular, with a market share of 27 percent (in 2015) (Pavel and Blagoeva, 2018).

Knowledge and gaps regarding the environmental impact of wood foam

Wood foam is 100 percent cellulose-based; thus, it is fully biodegradable. At the end-of-life stage, it can be recycled with paper or composted. Alternatively, it can be used as a source of energy.

Policies and incentives that enable the development of wood foam

In the United States of America, some states and municipalities have banned the use of expanded polystyrene for packaging food and beverages (Ivanova, 2019). The material has also been banned or will soon be banned in countries such as Zimbabwe (Mahvunga, 2018), Haiti (UNEP, 2018), Costa Rica (Cockburn, 2019), and in nine countries in the Caribbean (UNEP, 2019b), among others.

Relevant research and innovation initiatives related to wood foam

Wood foam products are currently under development but demonstrate potential to substitute non-sustainable materials such as polystyrene, polyurethane and polyisocyanurate. To date, there is no other fully biodegradable cellulose-based foam material (Fraunhofer Institute, 2020; Ritter, undated). The development of this product is especially important considering the pollution caused by plastic packaging, polystyrene and other fossil-based products that are not discarded or processed correctly at the end-of-life. Thus, having a material that can be easily recycled and that is fully biodegradable is an important step towards sustainability.

4.3 Bioplastics

Product description and required feedstock

There are several types of plastics that can be produced from bio-based sources (Figure 4.7), from first, second and third-generation feedstocks. First-generation feedstocks are carbohydrate-rich crops that can be consumed by animals (feed) and humans (food) (e.g. corn, potato, sugarcane and sugar beet). Second-generation feedstocks are crops and plants that are not suitable for food or feed (e.g. trees), or that are waste from first-generation feedstock (e.g. bagasse and waste vegetable oil). Lastly, third-generation feedstock comes from algae.

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Figure 4.7. Bioplastic granules and packaging

Bioplastics are usually produced using first-generation feedstock. However, the forest industry has also been investing in the development and manufacture of bioplastics from second-generation feedstock. In this case, the industry is focused on using industrial side streams, especially from the pulp and paper industry.

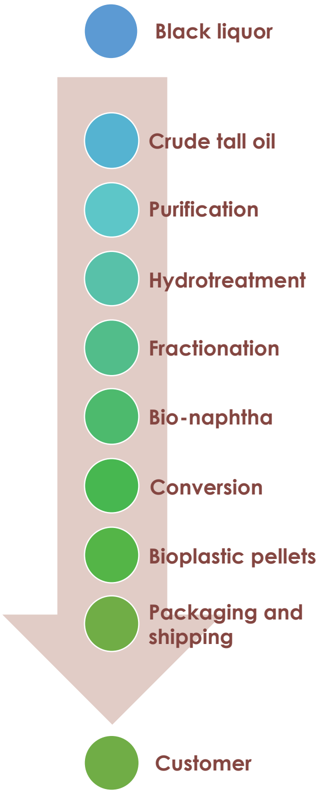

Figure 4.8. Simplified production process of bioplastics from crude tall oil

One of the side streams currently used in the production of bioplastics is tall oil. This by-product from the pulping process has always been used as a source of energy for the industry. However, value can be added to crude tall oil by fractionating it into several chemical compounds. One of these derivates is naphtha, which can be used in the production of biodiesel and bioplastics (De Bruycker *et al.*, 2014; Mäntyranta, 2020c) (Figure 4.8). Some companies convert the sugars found in wood into monoethylene glycol to produce bioplastic films as a substitute for the fossil-based plastic coating in liquid carton containers. Besides using a renewable raw material that comes from industrial side streams, these bioplastics contribute to circularity as they are recyclable with cardboard.

Another second-generation feedstock that can be used to produce bioplastics and polyurethanes is lignin (Wang *et al.*, 2019). Currently, about 50 million tonnes of kraft lignin are produced worldwide each year (Lettner *et al.*, 2018), but it is estimated that only 1–2 percent is recovered and used as raw material for products (Lora and Glasser, 2002). Some companies are taking advantage of the availability of this feedstock to produce bioplastics for several uses. In agriculture, for example, the use of single-use plastics in mulch films and containers for seedlings is standard practice. These plastics cannot be recycled and end in landfills after one crop season. Biodegradable plastics made from lignin sourced from the wood industry are being produced to reduce plastic pollution in the field. The advantage of lignin-based plastic over other bioplastics (e.g. from corn or potato starch) is that it takes longer to biodegrade (Hammerich, 2018), making it suitable for use in agriculture. Other bioplastics are being further developed to use paper sludge (a waste from the paper industry) as feedstock, or other by-products from the industry. The forest industry thus offers many feedstock options for bioplastics, especially when focusing on better use of undervalued by-products, residues and waste.

These new bioplastics from forest-based sources are suitable for both injection moulding, to produce hard plastic containers, and blown film and cast film extrusion lines, to produce flexible packaging. These bioplastics have the same characteristics as fossil-based plastics. When produced as pellets for injection moulding, they offer high transparency and clarity, and they can be dyed. When produced as films, they are clear, transparent and easy to use in thermoforming.

Current global demand and production

Bioplastics produced with feedstock from the forest industry are still at the early stages in terms of volume produced and development of technology and the production process. Companies investing in the development of wood-based bioplastics are mostly located in Europe (e.g. Finland, the United Kingdom of Great Britain and Northern Ireland, Belgium, the Netherlands) and in North America. All types of bioplastics considered – the majority being produced from first-generation feedstock – they represent only 1 percent of the total volume of plastics produced annually (around 335 million tonnes) (Gyekye, 2019). The current production capacity of second- and third-generation feedstock bioplastics is 2.3 million tonnes and is estimated to grow to 4.3 million tonnes by 2022 (Gyekye, 2019).

One food manufacturer has been using beverage cartons with bioplastic films since 2019, putting on the market more than 40 million of the 100 percent wood-based packages that year. According to the company, merely substituting bioplastics in the beverage cartons they produce will reduce fossil-based plastic consumption by 180 000 kilograms per year (Packaging Europe, 2019). However, one of the issues with increasing bioplastics production is finding enough raw material, as even access to adequate secondary feedstock may be difficult (Gyekye, 2019). These constraints concern finding the adequate feedstock (i.e. consistent and with the desired properties) at an adequate distance from the biorefinery, and possible competition for raw material with other bio-based products.

Fossil-based or GHG-intensive products that wood-based bioplastics can potentially displace

Forest-based bioplastics are a substitute for several types of fossil-based plastics, such as polyethylene and polyurethane. These bioplastics are technically equivalent to their fossil-based counterparts (European Bioplastics, 2020).

Knowledge and gaps regarding the environmental impact of wood-based bioplastics

Forest-based bioplastics have the potential to solve some of the current problems with fossil-based plastics. The world currently produces over 400 million tonnes of plastics per year, 36 percent of which are used in packaging (Geyer, Jambeck and Law, 2017). More than 75 percent of the global plastic production becomes waste each year (Geyer, Jambeck and Law, 2017). Moreover, plastics are non-renewable products from fossil sources.

One of the great advantages is using raw material from a renewable source as feedstock, especially from industrial side streams and waste. Some bioplastics, such as the plastic films that cover cardboards and cartons, can be recycled with paperboard, helping improve the circularity of these products. Finally, there are biodegradable lignin-based plastics, which can substitute fossil-based plastics that would end up in the landfills.

Policies and incentives that enable the development of wood-based bioplastics

Many countries have taken measures to ban the production, importation and use of single-use plastics. In Africa, most countries instituted a total ban on certain types of single-use plastics, with more than half of the countries implementing measures between 2014 and 2017 (UNEP, 2018). In Europe, the European Union Directive 2015/720 proposes measures to reduce the consumption of lightweight plastic bags, setting national maximum consumption targets. The European Commission has adopted a strategy to reduce the generation of waste from single-use plastics and ensure that all plastic packaging is recyclable by 2030 (European Commission, 2018a). Costa Rica is striving to become the first country in the world to eliminate all types of single-use plastics by 2021 (UNEP, 2018).

Relevant research and innovation initiatives related to wood-based bioplastics

Besides the bioplastics previously mentioned in this chapter, there are many other technologies and products under development as wood-based bioplastics are still in their infancy. Securing feedstock, scaling up and optimizing the production process, and fulfilling circular economy principles (e.g. recyclability and compostability) are some of the challenges that must be addressed as next steps in the development of wood-based bioplastics.

4.4 Wood-based composites

Product description and required feedstock

Wood-based composites, or wood-thermoplastic composites, are products made with wood input of various sizes (flour, fibres, particles, chips or solid wood) and a binding agent or thermoset polymer. These products were created to reduce the plastic content in goods, while conferring a more natural appearance (Carus and Partanen, 2019). Wood-based composites have been used for several decades as construction material (in decking, siding, roofing, etc.). These durable products combine the workability of wood, but have higher resistance to water, higher overall durability and require less maintenance. Nowadays, wood-based composites are being used to produce a large variety of products, from small disposable products, such as beverage straws, to furniture and large heavy-duty objects (Figure 4.9).


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Figure 4.9. Products made of wood-based composites

Some companies, concerned about the sustainability of resources and aiming to steer away from the use of plastics, started investing in the production of wood-based composite with a high percentage of bio-based raw materials that can be mechanically recycled, or that are compostable or biodegradable. Some of the new wood-based composites are made with bio-based binders (such as polypropylene or polylactide) (Mäntyranta, 2020c) or with binders that are fully biodegradable. The simplified production process of a generic wood-based composite is presented in Figure 4.10.

Figure 4.10. Simplified production process of a wood-based composite product

Because of the large variety of uses of wood-based composite products, the raw materials and the production process vary according to the requirements for the final product. Some products may use logs or solid wood as raw material, while the source for others may be industrial side streams. Wood flour may be used to confer an appearance similar to ceramic or moulded plastics. Wood fibres are frequently used when the workability and mechanical properties are important elements in the final product. If products are designed to have a more natural appearance, larger chips and fibre bundles may be used. Other important aspects in the production of wood-based composites are the choice of binding agent or polymer, and the use of additives to improve bonding, product performance (e.g. ultraviolet light stabilizers, flame retardants), and processability.

Current global demand and production

In Europe, there are about 35 bio-based composite producers, from nine countries. In 2018, production was nearly 470 000 tonnes of bio-based composite (nova-Institute, 2019). The largest producer of these granulates in Europe is Portugal, where the production of cork-based composites was over 50 000 tonnes in 2018. Other important producers of bio-based composites in Europe, in terms of volume, are Belgium, Germany, France, Finland and Sweden (Carus and Partanen, 2019). Among the bio-based materials used as reinforcement in composites, cork has the largest share (around 60 percent), followed by wood and cellulose fibres (over 25 percent) and other natural fibres (around 15 percent) (Carus and Partanen, 2019).

Fossil-based or GHG-intensive products that wood-based composites can potentially displace

These wood-based composites can substitute plastics used to manufacture durable products (such as containers, hangers, countertops, etc.) or single-use products (such as beverage straws). For certain applications, wood-based composites can also be an alternative to durable yet non-renewable and GHG-intensive materials such as natural stones (e.g. granite, marble) and porcelain.

The bio-based materials in the new wood-based composites are used as reinforcement and fillers to reduce the proportion of fossil carbon in the products, while increasing the proportion of renewable carbon. The share of bio-based carbon can be increased by substituting fossil-based plastics and resins by bio-based binders.

Knowledge and gaps regarding the environmental impact of wood-based composites

One type of wood-based composite, intended for durable, waterproof products, has a lower carbon footprint than its ceramic counterpart. According to a Life Cycle Assessment (LCA), the carbon footprint over the whole product life cycle is 55 kg lower per unit than ceramic (Nurmio, 2018). At the end of the life cycle, some new wood composites can be mechanically or chemically recycled. Others are compostable in industrial facilities or fully biodegradable, not releasing any microplastics in the environment.

Policies and incentives that enable the development of wood-based composites

Some new wood-based composites are being produced to help solve the problems caused by plastic pollution. As with bioplastics, the development of these wood-based composites is boosted by the ban on plastic and polystyrene packaging and other single-use products (UNEP, 2018).

Relevant research and innovation initiatives related to wood-based composites

Companies developing and producing new wood-based composite focus on eco-design, which considers the whole life cycle of the materials. They are developing products that minimize the consumption of energy and natural resources, as well as the production of waste and GHG emissions. New wood-based composites can be mechanically or chemically recycled, and are compostable following standard EN 13432, which requires the material to biodegrade fully in less than 12 weeks.

Innovations in wood-based composites are not restricted to improvements in raw materials and production processes. Some products come from brand new concepts and are being developed as an alternative to traditional materials used in applications such as smart surfaces (or tactile surfaces) and transparent wood (see Innovations in wood-based composites are not restricted to improvements in raw materials and production processes. Some products come from brand new concepts and are being developed as an alternative to traditional materials used in applications such as smart surfaces (or tactile surfaces) and transparent wood (see Box 5).

Box 5: Transparent wood as an example of a new wood-based composite

Transparent wood is one type of innovative wood-based composite material with several potential applications. In recent years, methods for impregnating solid wood with polymers to create pliable wood or transparent wood have been developed and tested. These innovative products are still in the early stages of development, with an estimated Technology Readiness Level (TRL) (NASA, 2012) of 4–5. Possible uses for this innovative material are in construction, solar panels, electronics, light transmitting structures and heat shielding materials.

One of the methods was developed by researchers from KTH Royal Institute of Technology in Sweden, and the University of Maryland in the United States of America. The method consists in delignifying blocks of wood while maintaining the wood structure, and adding polymers (poly(methyl methacrylate) and epoxy) to the cell walls and cavities, conferring the wood a translucent effect (Zhu et al., 2016). Transparent wood has optical transmittance varying from 15 percent (tested on 0.7 mm-thick pieces) (Yaddanapudi et al., 2017) to over 85 percent (tested on 5 mm-thick elements) (Li et al., 2016). It is shatterproof and load-bearing, has high optical transmittance, low thermal conductivity and low density, and is also more insulating than glass (Figure 4.11). The improved mechanical properties result from a combination of the intact cellulose structure in the cell walls and the inclusion of resin.


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Figure 4.11. Transparent wood

Variations of the method were created, slightly changing the functionalities of the material. In one method developed by Montanari *et al.* (2019), the lignin is removed and acrylic mixed with polyethylene glycol is injected in the wood. Acrylic is non-biodegradable and water-resistant, while polyethylene glycol absorbs energy and melts when heated – and hardens when temperatures decrease – releasing energy in the process. This material could be used in construction, absorbing energy from the sun during the day and releasing it into the interior, make the building more energy efficient.

In another initiative, also by KTH Royal Institute of Technology, lignin and hemicelluloses are removed from thin layers of wood that are compressed and dried. This material becomes 20 times thinner and 25 times stronger than the original wood. The mechanical properties are also higher than most other materials (strength-to-weight) such as steels, alloys and plastics. To demonstrate the possibilities involving this technology, a translucid wood-based electronic circuit with carbon fibres derived from lignin was produced (Fu, Chen and Sorieul, 2020). According to the researchers, this technology could be applied to wearable devices, smart packaging and sensors in the future.

4.5 Wood-based fibres for textiles

Product description and required feedstock

Wood-based textiles are categorized as man-made cellulosic fibres, a category that includes viscose, acetate and lyocell, among others. The production process using these traditional technologies usually involves dissolving wood pulp and wet spinning. Newer technologies for textile fibre production stray away from the use of harsh chemicals, opting for a combination of mechanical treatment and non-harmful chemicals, such as one type of ionic liquid. In some cases, these new fibres are not even classed as man-made cellulosic fibres because there is no dissolving of wood at any stage of the process.

Lyocell has recently drawn attention as a bio-based environmentally friendly production method, and wood fibre has been promoted as a natural fibre preferred to fossil-based fibres and even cotton. The fibre has a highly crystalline structure that allows good wet and dry strength. It has a higher dry tenacity (strength) value than viscose fibre and is almost equivalent in strength to polyester fibre. It is the only regenerated cellulose fibre with a wet tensile strength higher than cotton. Compared to viscose fibre, lyocell has a significantly reduced elongation (elasticity). It can be blended, dyed and spun into fine count yarns. Lyocell is suitable for nonwovens due to its high strength, biodegradability, easy processing, absorbency and potential to fibrillate (Borbély, 2008).

The production of lyocell uses nontoxic N-methylmorpholine-N-oxide hydrate as solvent, 99 percent of which can be recovered and recycled. The dissolving grade wood pulp is mixed into a paste with the solvent, going through a high temperature dissolving unit and forming a clear viscous solution, which is filtered, pumped into spinnerets, and spun into the diluted solvent, where the cellulose fibres precipitate. The fibres are washed, dried, lubricants (such as silicone or soap) applied, carded (to separate the strands), and baled (Borbély, 2008).

Some of the newer technologies (e.g. Spinnova, Metsä fibre or Ioncell) have yet to become operationally feasible at a commercial scale, but they represent more sustainable alternatives to current textile production. These new technologies can solve some of the problems associated with the production of fossil-based fibres (e.g. polyester) and GHG-intensive fibres (e.g. cotton) (Ellen MacArthur Foundation, 2017). These new processes also aim to decrease water and energy consumption during production, reduce GHG emissions, and improve circularity in the textiles value chain (Antikainen *et al.*, 2017), which are common issues when GHG-intensive feedstock is used.

The new wood-based fibres for textiles have similar properties to cotton, viscose and other natural fibres, such as lamb wool (Figure 4.12). Some are stronger than viscose and the texture is similar to cotton or lyocell. These new fibres can be spun into yarn and knitted, wove into fabric, or used for nonwovens. The fibres can be used on their own or blended with fibres from other sources, such as cotton, wool and other man-made cellulosic fibres. Some new wood-based fibres can be dyed before the spinning process, which reduces water consumption. Pilot plants have been producing, testing and improving the new wood-based fibres for textiles (Mäntyranta, 2020c; Salmela, 2020), and production at the commercial scale is set to start in 2022.

Figure 4.12. Wood-based staple fibre and textile

The production process varies according to the type of wood-based fibre being produced, but a simplified method is presented in Figure 4.13.

Figure 4.13. Production process of wood-based staple fibre for textiles

One new technology does not involve the dissolving of pulp – the result is not therefore considered a man-made cellulosic fibre. The raw material is either pulp from certified wood or cellulosic waste streams. The wood goes under mechanical treatment before being converted to kraft pulp. It then goes through a refining process to transform the pulp into a paste of microfibrillated cellulose. This fibre suspension goes into a process using rheology to align the microfibres. This material is transformed into staple fibre through dry spinning. The mechanical properties and the feel are similar to cotton. After the end of the fabric life cycle, it can be ground back into microfibrillated cellulose and reused in the process to produce new staple fibre.

Current global demand and production

The current global textile fibre market amounts to 111 million tonnes per year. It is estimated that in 2030 it will reach 146 million tonnes (Textile Exchange, 2020) (Figure 4.14). In 2019, 52 percent of the global fibre production volume was polyester, 23 percent cotton, 6.4 percent man-made cellulosic fibres (including viscose and lyocell), and 18.6 percent others (Textile Exchange, 2020) (Figure 4.15).

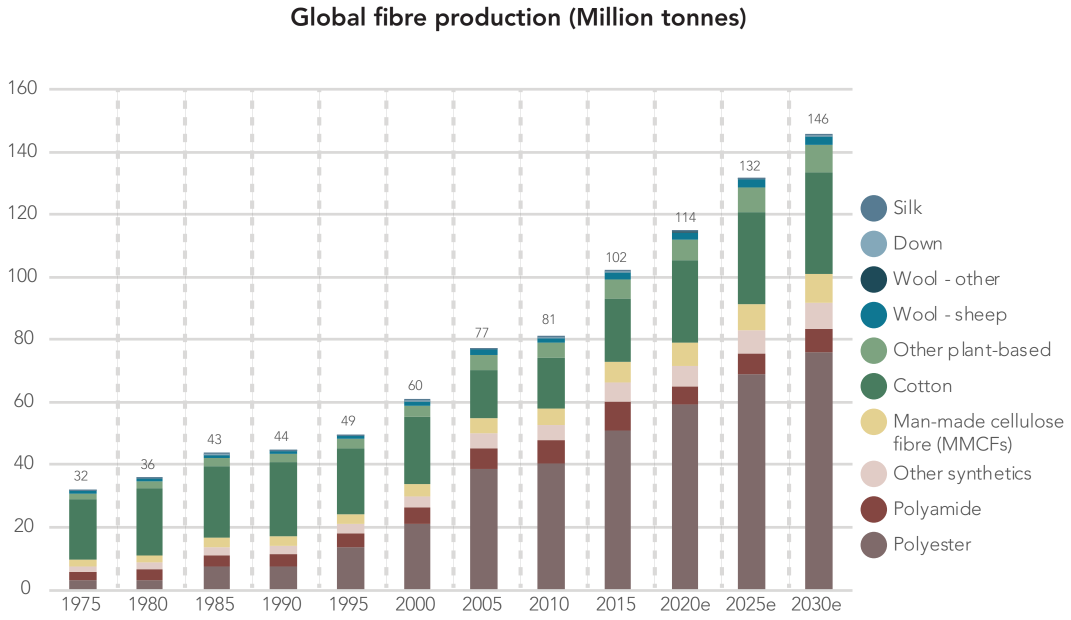

Figure 4.14. Global fibre production trend
Source: Textile Exchange (2020)

Lyocell was the third most used man-made cellulose fibre type after viscose and acetate in 2019. It had a market share of around 4.3 percent of all man-made cellulosic fibres in 2019, with a production volume of roughly 0.3 million tonnes. The compound annual growth rate of lyocell from 2017 to 2022 is estimated at around 15 percent. This means that lyocell is expected to grow faster than other man-made cellulosic fibres (Textile Exchange, 2020).

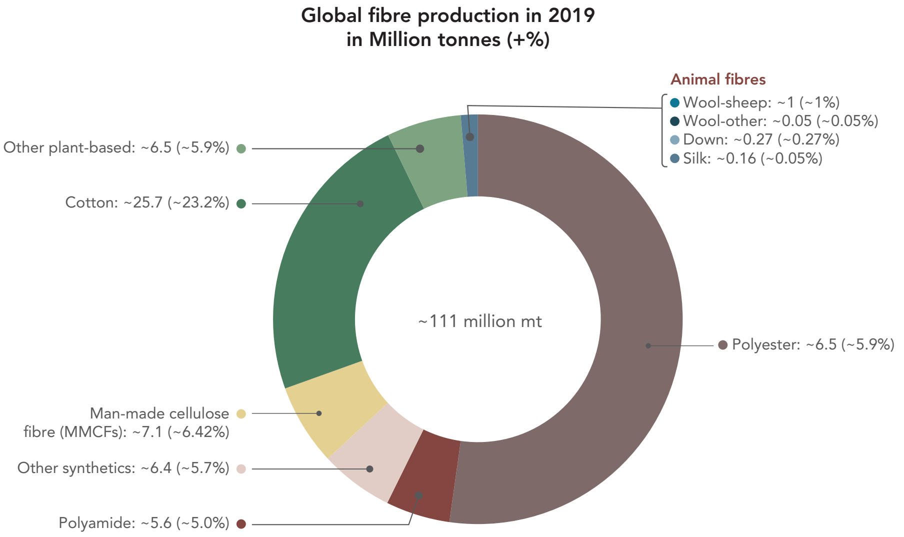

Figure 4.15. Global fibre production
Source: Textile Exchange (2020)

In 2019, Lenzing announced plans to build the world's largest lyocell plant in Thailand, with annual production capacity of 100 000 tonnes. Lenzing also started a joint venture to produce protective equipment for the COVID-19 crisis (Textile Exchange, 2020). Sateri, the largest viscose producer, started manufacturing lyocell in 2020. Its parent company, Royal Golden Eagle, has announced plans to invest USD 200 million over the next ten years in cellulosic textile fibre research and development (Textile Exchange, 2020).

Fossil-based or GHG-intensive products that wood-based textiles can potentially displace

The new wood-based fibres can substitute viscose and cotton, depending on the treatment given to the fibres and the textile industry's requirements. However, unlike conventional man-made cellulosic fibres and cotton, the new technologies are focusing on the development of processes with a lower environmental impact, using nontoxic chemicals or no chemicals at all, functioning as a closed loop, and even permitting the use of old textiles, cardboards and agricultural waste as feedstock.

There has been concern regarding the release of microplastics from synthetic textiles into the environment through wear and tear during the normal product life cycle. It is estimated that about 67 million tonnes of synthetic fibres are produced each year (Textile Exchange, 2020). Nearly 35 percent of the global releases of primary microplastics into the world's water sources are attributed to the regular use and laundry of synthetic textiles (Boucher and Friot, 2017). Therefore, substituting synthetic and non-biodegradable textile fibres with more sustainable options would help reduce pollution caused by microplastics.

These new textile fibres, whether pure or blended with cotton, can also be recycled using the same production process. When blended with polyester or other fossil-based materials, filtering is required after dissolving the old textiles. Manufacturers are also concerned with producing recycled fibres that are also durable. According to Spinnova (2021), the recycling process itself can improve the quality of the final material. The new wood-based fibres for textiles also have the advantage of being biodegradable, but details on the conditions and time for biodegradability are not yet available.

Knowledge and gaps regarding the environmental impact of wood-based fibres for textiles

Man-made cellulosic fibres (e.g. viscose and lyocell) have a lower environmental impact than cotton, polyester and polypropylene fibres, which is attributed to the use of renewable energy during the production process, lower use of chemicals, lower GHG emissions, and lower water consumption (Shen, Worrell and Patel, 2010). In addition, the new wood-based fibres for textiles have other benefits such as the use of non-organic compounds during production or the complete absence of dissolving chemicals, reduced water consumption, and production in a closed loop (Antikainen *et al.*, 2017).

Policies and incentives that enable the development of wood-based fibres for textiles

Growing concern from consumers regarding the release of microplastics from synthetic textile use, as well as the environmental impacts of cotton and synthetic textile production (Ellen MacArthur Foundation, 2017) are driving the development of more sustainable textile fibre alternatives. Pressure from the public sector is necessary to establish regulations, standards and economic incentives to encourage the development of more sustainable products and to foster the adoption of more sustainable practices by the textile industry, especially regarding circularity aspects (Hugill, Ley and Rademan, 2020). The European Commission is investigating possible actions to limit the release of microplastics into the environment from plastic production and the use of common products (e.g. tyres and textiles). The new Drinking Water Directive, for instance, will foster the development of methodology to measure microplastics in water and, subsequently, provide the information the Commission requires to regulate the manufacture of products that release microplastics (Council of the EU, 2020).

Relevant research and innovation initiatives related to wood-based fibres for textiles

When compared to existing technologies for producing man-made cellulosic fibres, innovation regarding new wood-based fibres mostly relates to the staple fibre production process. The absence of harsh chemicals, either by using a type of ionic liquid or mechanical treatment, is an important step towards sustainability. Other relevant aspects are the recyclability and complete biodegradation of these new wood-based fibres.

4.6 Summary

New technologies that transform biological resources into new bio-based products are being developed to replace fossil-based products and non-renewable raw materials. Two of the most ubiquitous polymers found in nature are important components that can be used to produce many innovative bio-based products, from adhesives to plastics to textiles (Sillanpää and Ncibi, 2017). The development of innovative forest-based products follows increasing awareness among governments, companies and consumers regarding the widespread use of fossil-based and GHG-intensive materials in products (Hurmekoski *et al.*, 2018). The new technologies aim to increase the added value of wood products and decrease the carbon and water footprint of products and processes, reduce pollution, and waste generation, and improve circularity. This review's intention is to describe some of the emerging and novel products with potential for substitution. Far from being exhaustive, the list of products reviewed in this study aims to highlight some of the up-and-coming products and technologies that are most likely to become known to the public in the near future or that will continue to increase their market share (summarized in Table 4.2).

Table 4.2. Summary of the selected innovative forest-based products

	Innovative forest-based products					
	CLT	**LVL**	**Wood foam**	**Bioplastics**	**Composites**	**Textile fibre**
Type of product	Engineered wood	Engineered wood	Multiple uses	Bioplastics	Multiple uses	Textiles
Potential uses	As structural elements, as well as ceilings, floors and walls	As structural elements, as well as ceilings, floors and walls	Insulation material in walls, furniture and doors; in packaging	Packaging (including food grade)	As construction materials (e.g. decking, sidings, roofing), disposable products, furniture, heavy-duty objects	Woven and nonwoven textiles
Current global demand and production	Global production around 2.0-2.5 million cubic metres/ year	Global production around 5 million cubic metres/year	Varies according to the application	Global production around 2.3 million tonnes/ year (2nd and 3rd generation feedstock)	Production in Europe around 470 000 tonnes/year	Global production is around 111 million tonnes/year
Feedstock required	Usually coniferous sawnwood, although deciduous can also be used, or structural composite lumber	Usually coniferous logs, but deciduous logs can also be used	Wood fibre, either from softwoods or hardwoods	Industrial side streams and by-products, such as tall oil, wood sugars and lignin	Wood flour, fibres, particles, chips or solid wood (depending on the final product)	Wood pulp from kraft process or other high-content cellulose feedstock
Fossil-based or fossil-intensive products that the wood-based product can potentially displace	Concrete, steel and bricks	Concrete, steel and bricks	Polystyrene, polyurethane	Fossil-based plastics (e.g. polyethylene and polyurethane)	Fossil-based plastics	Polyester, polyamides, acrylics, cotton, etc.

Table 4.2. Summary on the selected innovative forest-based products (continued)

	Innovative forest-based products					
	CLT	**LVL**	**Wood foam**	**Bioplastics**	**Composites**	**Textile fibre**
Knowledge and gaps regarding the forest-based product's environmental impact	At the end-of-life stage, in general, CLT can be mechanically recycled or used as a source of energy, and the wood portion is biodegradable.	At the end-of-life stage, LVL can be mechanically recycled or used as a source of energy. The wood portion of the product is biodegradable.	Cellulose-based wood foam is fully biodegradable or can be used as a source of energy	Some bioplastics are recyclable with carton or with fossil-based plastics, others are fully biodegradable	Some wood composites can be recycled, others are compostable or biodegradable and do not release microplastics	Production is a closed loop without harsh chemicals; fibres are biodegradable and recyclable
Policy and other incentives that enable the forest-based product's development	Changes in building codes National incentives from country governments Public procurement rules and regulations promoting buildings with lower carbon footprint	Changes in building codes National incentives from country governments Modifications to standards Public procurement regulations promoting buildings with lower carbon footprint	Ban on expanded polystyrene for packaging Country- and regional-level strategies to reduce polystyrene use	Ban on single-use plastics Country- and regional-level strategies to reduce single-use plastic use and the generation of waste from these sources	Ban on single-use plastics Country- and regional-level strategies to reduce single-use plastic use and the generation of waste from these sources	Concerns with the release of microplastics from textiles EU's new Drinking Water Directive Legislation on registration, evaluation and restrictions on chemicals
Relevant research and innovation initiatives related to the product	Substitution of synthetic adhesives by bio-based ones or by wooden dowels	Substitution of synthetic adhesives by bio-based ones	100 percent cellulose-based foam Fully biodegradable foam material	Use of industrial side streams as feedstock Biodegradable plastics from lignin Bioplastics from tall oil; can be recycled with cardboard	Fully biodegradable wood-based composites Use in applications such as smart surfaces and transparent wood	Production without harsh chemicals Fibres are biodegradable and recyclable

Take-home messages

- The use of engineered wood products such as CLT and LVL contributes to lowering a building's carbon footprint by displacing fossil-based materials, reducing waste during construction, reducing construction time and the cost per constructed area, among other things. In addition, the carbon sequestered from the atmosphere is stored in a durable product, reducing GHG emissions (Churkina *et al.*, 2020; D'Amico, Pomponi and Hart, 2021).
- Wood foam is a possible substitute for fossil-based and GHG-intensive materials used in construction, such as polystyrene and polyurethane. It can also be used in the packaging industry, displacing polystyrene, with the advantage of being recyclable and biodegradable.
- For bioplastics, feedstock from the forest industry mainly comes from side streams and ranges from tall oil to sugars to lignin. The technology used to produce bioplastics from forest resources is viable and applicable on a large scale, but it may face tough competition not only from conventional materials but also from other bioplastics. Nonetheless, forest-based bioplastics and composites may have their place on the market, in the form of durable products or to exploit desirable characteristics, such as full biodegradability.
- Wood-based textiles face competition from synthetic fibres (e.g. polyester) and from natural but resource-intensive fibres (e.g. cotton). However, the new wood-based fibres are not only adequate substitutes from a technical standpoint, but they have important advantages regarding eco-design, where sustainability of the natural resources and circularity are part of the product conception.

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5 Opportunities offered by substitution with forest products

5.1 Sustainability impacts over a forest product's life cycle

Sustainability has been a core principle in forestry for centuries. While initial understanding of the concept focused on sustained yield, it has since extended greatly to include the economic, social and environmental dimensions covering all activities along the forest product value chain. It also considers other uses of forests and their products and services. This chapter reviews the quantitative and qualitative understanding of the environmental impacts and benefits of substituting fossil-based and GHG-intensive products with forest products (mainly wood products), and how substitution contributes to the SDGs.

The forest product value chain includes multiple stages. The forest production phase is a critical stage where many sustainability impacts occur. The production of forest products requires raw materials and the production and extraction of these raw materials from forests have economic, social and environmental impacts. The enhanced use of forest products would therefore intuitively incur a risk of increased pressure on forests and forest-dependent people, while raising concerns over the degradation of forests and ultimately leading to biodiversity loss and a reduction of carbon stocks and storage biomass decline. In the context of a developing bioeconomy, a shift to improved, more sustainable and climate-smart forest management is needed (Box 6: Climate-Smart Forestry) to ensure that forest productivity can be maintained or enhanced under climate change.

Sustainability impacts during the processing, manufacturing, use and disposal stages of the production chain are typically estimated by LCA studies (Adhikari and Ozarska, 2018; Klein *et al.*, 2015; Mäkelä, 2017). Such studies compile and evaluate the inputs, outputs and the potential environmental impacts of a product system during its lifetime. These studies thus evaluate the energy, water and chemicals that are needed and used to process or manufacture the products and they provide information on the emissions of pollutants into air and water, and on by-products which, in the forest industry, are often used as raw materials in other processes or as a source of energy (Adhikari and Ozarska, 2018; Mäkelä, 2017). Existing LCA studies on forest products indicate that there are climate-related impacts from processing, manufacturing, use and disposal of products. There are also impacts related to eutrophication, acidification, photochemical oxidant formation and human toxicity, but understanding of these impacts is still limited (Klein *et al.*, 2015; Mäkelä, 2017). Possible ways to minimize environmental impacts include changes in energy consumption behaviour, promotion of renewable energy, improved sawing and sawmilling practices, proper wood waste management, use of less toxic chemicals for the treatment of wood products, and use of energy efficient and environment-friendly drying techniques and energy sources (Adhikari and Ozarska, 2018).

Box 6: Climate-Smart Forestry

The Paris Agreement requires major societal and economic reforms to ensure that the global average temperature remains 2 °C below pre-industrial levels. Forests and forestry can play an important role in this context through a wide set of measures, adapted to local circumstances. Unfortunately, their role in mitigation and adaptation are often not considered together in national strategies for implementing actions under the Paris Agreement. Climate-Smart Forestry has been introduced as a holistic approach to guide forest management in Europe (Bowditch *et al.*, 2020; Jandl *et al.*, 2018; Nabuurs *et al.*, 2017; Verkerk *et al.*, 2020; Yousefpour *et al.*, 2018), but the approach is of global relevance (e.g. Bele, Sonwa and Tiani, 2015), with the aim of connecting mitigation with adaptation measures, enhancing the resilience of forest resources and ecosystem services, and meeting the needs of a growing population. Climate-Smart Forestry builds on the concepts of sustainable forest management, with a strong focus on climate and ecosystem services. It builds on three mutually reinforcing components (Verkerk *et al.*, 2020):

- Increasing carbon storage in forests and wood products, in conjunction with the provisioning of other ecosystem services;
- Enhancing forest health and resilience through climate change adaptive forest management; and
- Using wood resources sustainably to substitute non-renewable, carbon-intensive materials.

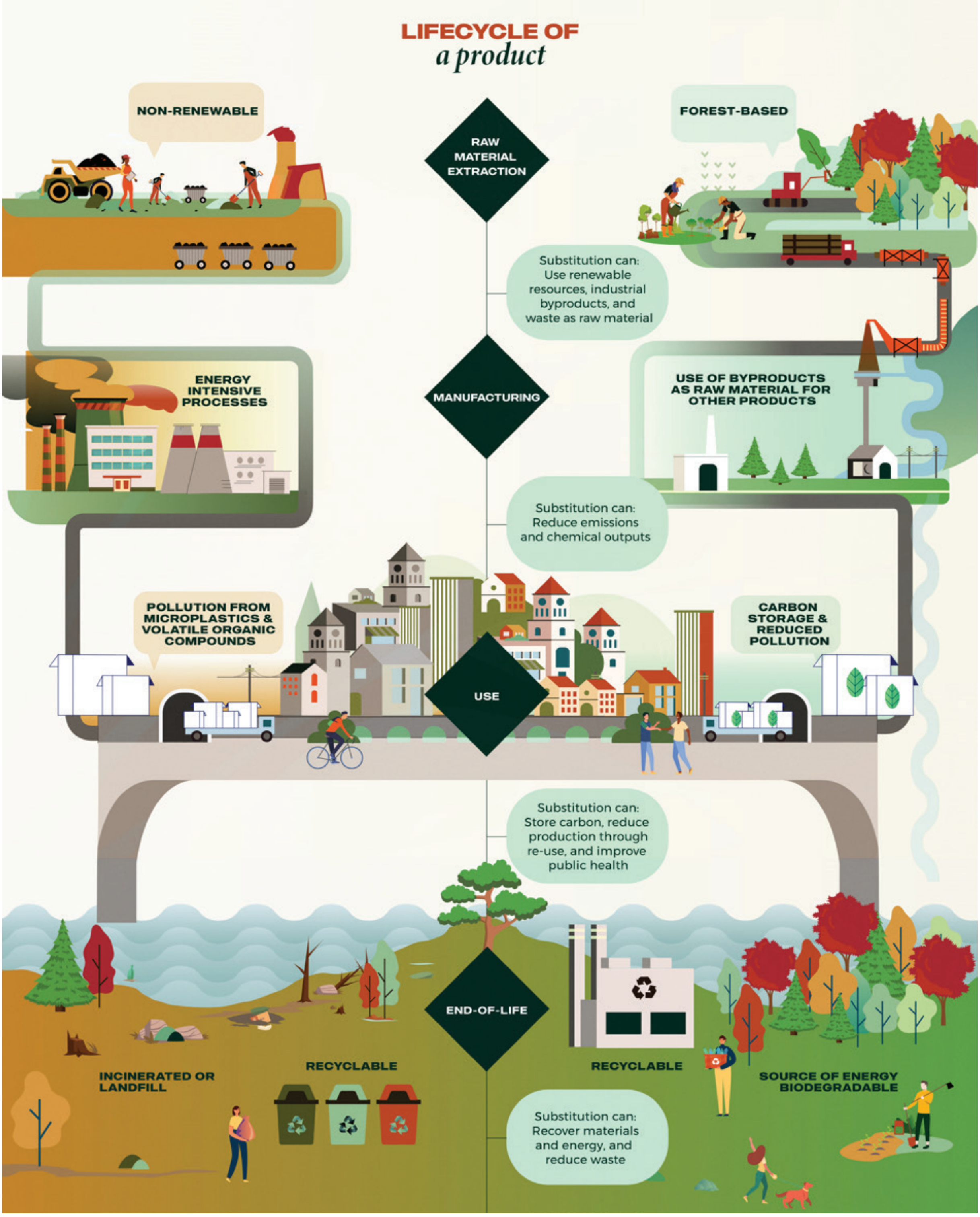
Climate-Smart Forestry aims at a mix of these by developing spatially diverse forest management strategies that acknowledge all carbon pools, emissions and removals simultaneously to provide longer-term and larger mitigation benefits, while supporting biodiversity and other ecosystem services. Such strategies should combine measures to maintain or increase carbon stocks in forest ecosystems and wood products, and maximize substitution benefits, while taking regional conditions into account.

In the developing bioeconomy, forests products may be used to substitute for products made from more emission-intensive, non-renewable materials. It is therefore important to look not only at the impacts of products made from wood, but also at the impacts of a functionally equivalent product made from other materials. Substitution can help tackle other associated global challenges such as environmental degradation – by encouraging the use of sustainably produced materials from renewable sources – and contribute to circularity by promoting the use of reusable, recyclable, and biodegradable products.

5.2 Greenhouse gas emission substitution

5.2.1 Estimating substitution effects

Product-level substitution effects can be estimated by comparing emissions of a GHG or other gas or substance over the life stages of a product designed from wood with a product made from other types of materials (Figure 5.1). To enable comparison of the substitution effects of



Substitution can: Use renewable resources, industrial byproducts, and waste as raw material

Substitution can: Reduce emissions and chemical outputs

Substitution can: Store carbon, reduce production through re-use, and improve public health

Substitution can: Recover materials and energy, and reduce waste

Figure 5.1. Life cycle stages of a product

different products or production systems, a substitution factor (or displacement factor) is typically used to express the emissions that would be avoided if a wood-based product were used instead of a product made from another material providing the same function. The overall substitution effects can then be estimated by combining information on the quantity of wood products produced or consumed, with the product-specific substitution factors.

There is no fixed way of calculating or reporting substitution factors. However, an approach that is frequently used in the literature was published by Sathre and O'Connor (2010), who reviewed GHG substitution factors and expressed them as:

$$SF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}} \qquad \text{Equation 1}$$

In this equation, $GHG_{non\ wood}$ and GHG_{wood} are the GHG emissions resulting from the use of non-wood and wood alternatives and WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood used in wood and non-wood alternatives. If the result of this equation is positive, a wood product leads to less GHG emissions compared to the non-wood (functionally equivalent) product.

Net CO_2 emission is typically the most important emission for climate effects, but emissions of other GHGs (e.g. methane emissions from landfilling, nitrous oxide from fossil fuels used in transport) can also have an important influence. By using the concept of global warming potential, the different GHG emissions can be converted to a commensurable unit, expressed as CO_2 equivalents of the different gases for a given timeframe (typically 100 years).

GHG substitution effects are typically reported in different units and can be expressed in terms of carbon (C), carbon dioxide (CO_2) or global warming potential (carbon dioxide equivalent, CO_2e), either per unit of mass of wood product, or volume. While it is possible to correct for these differences, a direct comparison of substitution effects reported in existing literature is complicated as studies vary in the extent that they cover different life cycle stages (Figure 5.1) and how they consider allocation of side streams. Carbon storage in forest biomass, soils and in the wood product, together with substitution, is crucial for a holistic understanding of the impacts of management and policy decisions on the forest carbon cycle. However, carbon storage and substitution are two different components that affect the carbon cycle; carbon storage refers to the addition of carbon to the forest or wood product carbon pool, while substitution refers to emissions avoided through the production, use and disposal of products.

Leskinen *et al.* (2018) conducted a systematic review of studies on substitution effects published before April 2018. The review included only studies that provided original substitution factors, or studies that contained emission data for a wood product and a functionally equivalent non-wood product that could be used to calculate substitution factors. Studies that relied on substitution factors from previous studies were excluded from the review unless they provided new information by, for example, expanding the system boundaries of the previous studies. In total, their review focused on 51 individual studies, yielding 433 separate substitution factors. In the present study, the same data collection criteria were used and expanded the database originally developed by Leskinen *et al.* (2018). The results are based on a total of 488 substitution factors from 64 studies; the results presented here are therefore an update of the results by Leskinen *et al.* (2018), based on a larger body of literature. Where necessary for unit conversions, default values from the Intergovernmental Panel on Climate Change (IPCC) were used, assuming an air-dry moisture content of 15 percent and excluding carbon storage effects. All substitution factors are reported in kilograms C avoided per kilogram of C in the wood product.

5.2.2 Product-level substitution effects

Overview of existing studies

Compared to the review by Leskinen *et al.* (2018), additional studies providing GHG emission substitution factors for products in countries covered previously were identified (Czech Republic, Poland, Portugal and Spain). Overall, most of the studies from which GHG emission substitution factors could be derived focused on the United States of America and Canada, and the Nordic countries in Europe (i.e. Finland, Sweden and Norway). There are several studies focusing on Asia (mainly China and Japan), just a few studies focused on New Zealand, Australia and South America (Brazil), and no studies focusing on Africa (Figure 5.2). All 64 studies providing information on GHG emission substitution factors include the production stage of the product life cycle and 40 studies also include the end-of-life stage. A smaller number of studies provided information on the GHG emission substitution effects of product use.

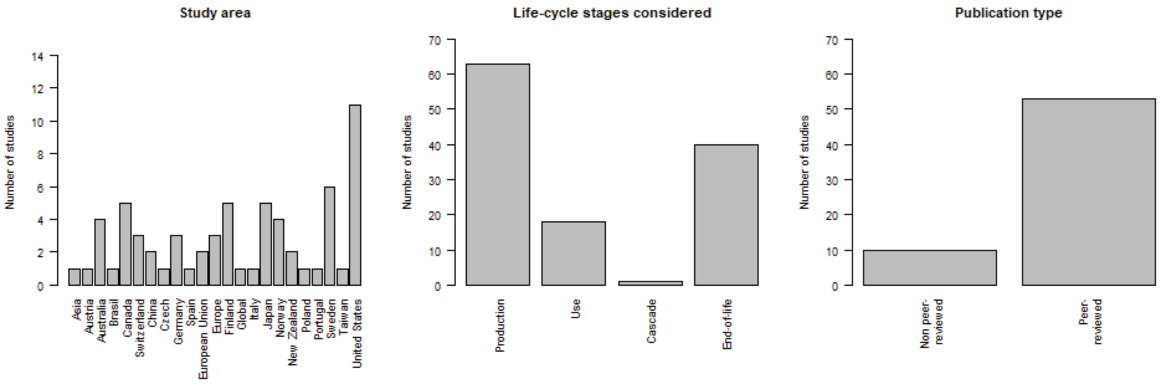


Figure 5.2. Information on the GHG emission substitution effects of wood-based panels
Source: Updated from Leskinen *et al.* (2018)

Over three-quarters of the GHG emission substitution factors derived from the literature related to the construction sector (Figure 5.3, left). Over half of the studies assessed GHG emission substitution effects by structural construction products such as buildings, civil engineering, walls, wood frames or beams. The remaining quarter of construction products considered related to non-structural products such as floor and ceiling covers, insulation material, window frames, doors and cladding. Substantially fewer GHG emission substitution factors were available for other product types (i.e. furniture, packaging and textiles) and especially for paper and chemicals.

Approximately one-third of the GHG emission substitution factors involved replacing wood for cement, concrete, ceramics or stone. A quarter of all the factors involved substituting wood for metals and alloys, mostly steel and aluminium (Figure 5.3, right). Approximately one-fifth of the factors related to plastics, for example polyethylene, polypropylene, polystyrene and polyvinyl chloride. Some factors did not relate to one specific non-wood material being replaced by wood, but to combinations of various materials.

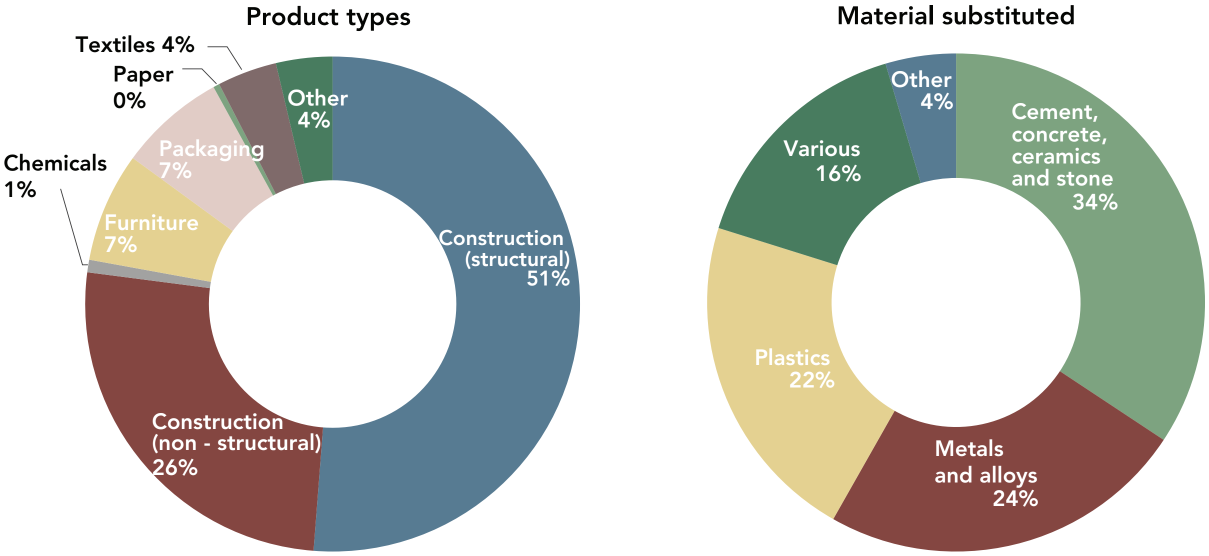


Figure 5.3. Summary of substitution factors used for product types and non-wood materials being substituted as per literature

Source: Updated from Leskinen *et al.* (2018)

GHG emission substitution factors

Overall, the 63 reviewed studies suggest a median GHG emission substitution effect of 0.9 kg C/kg C, which means that for each kilogram of C in wood products that substitute non-wood products, there is (according to substitution effects derived from the literature) an average GHG emission reduction of approximately 0.9 kg C. This value would correspond to approximately 1.7 kg CO_2/kg wood product or 0.9 kg CO_2/m^3 of wood product. Moreover, 91 percent of the substitution factors that include two or more life cycle stages have a value greater than zero. These findings indicate that wood products generally provide a positive contribution to climate change mitigation at the product level. The median substitution value is, however, of limited practical use otherwise as it is based on substitution effects reported in the literature and does not consider the extent to which these products are produced or consumed in forest product markets. It is also important to realize that the positive substitution values are the results of emission reductions that occur over the entire life cycle of a product and these emission reductions may occur at different points in time.

The overall substitution factor is subject to large variability, as 95 percent of the values range between -1.1 kg C/kg C and +5.2 kg C/kg C. As pointed out by Leskinen *et al.* (2018), an important reason for this is that these values are based on many different product types, non-wood materials that are substituted, production technologies, number of life cycle stages considered, and end-of-life management practices. For example, when focusing only on studies that considered two or more life cycle stages, the median substitution effect increases to 1.0 kg C/kg C. Furthermore, over 90 percent of the substitution factors that include two or more life cycle stages have a value greater than zero, thus emitting less GHG.

The substitution benefits from using wood over alternative non-wood products are largely gained from reduced fossil GHG emissions during the wood processing, product manufacturing and end-of-life stages of the wood product. The median substitution factor for the production stage was 0.6 kg C/kg C for a wood product and 0.5 kg C/kg C for the end-of-life stage. The few studies that provide estimates for the product use stage suggest a small but positive median substitution effect of 0.03 kg C/kg C. A very small number of studies provide information on substitution effects through cascading.

Substitution factors for the construction sector

As indicated above, about three-quarters of the studies reporting on substitution effects focus on products for the construction sector. The substitution factor derived from these studies generally indicates that, compared to non-wood products, the use of wood for construction purposes results in climate benefits. The substitution factors derived from the literature showed substantial variability (Figure 5.3); the median substitution factor for structural construction was 0.9 kg C/kg C wood product, with 95 percent of the values ranging between -0.9 kg C/kg C and +5.4 kg C/kg C wood product. The median substitution factor for non-structural construction was 1.2 kg C/kg C wood product, with 95 percent of the values ranging between +0.2 kg C/kg C and +5.1 kg C/kg C wood product.

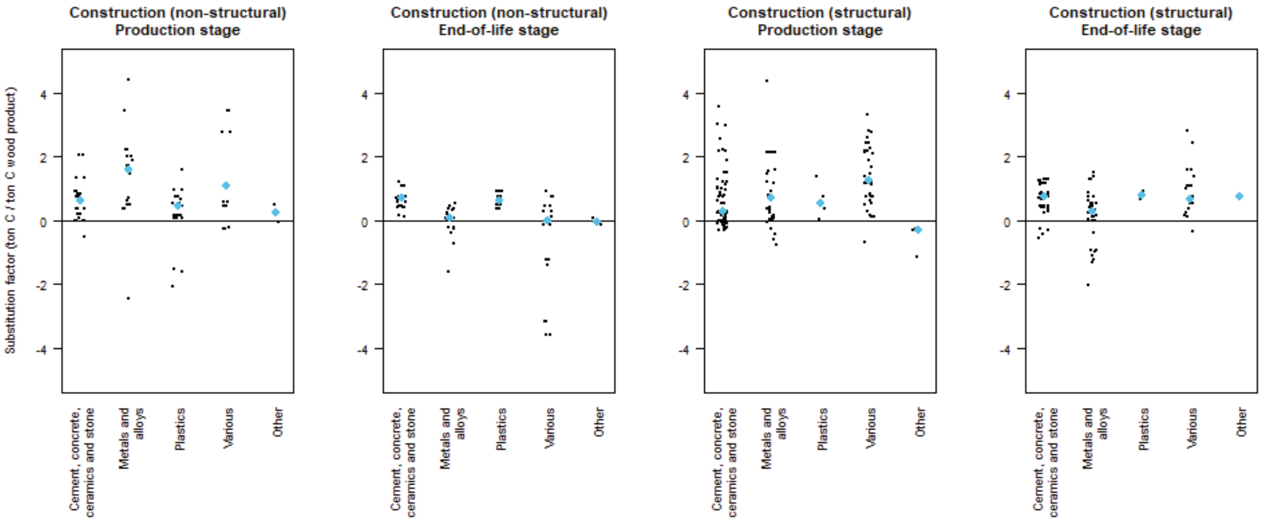


Figure 5.4. Overview of substitution factors derived for construction products (structural and non-structural) and by life cycle stage

Note: The black dots indicate individual substitution factors, while the blue dots indicates the median value.

Substitution factors for textile fibres

Textile fibres are considered a novel or new wood-based product with considerable potential for future development and attractive markets (Hurmekoski *et al.*, 2018). However, only two studies (Rüter *et al.*, 2016; Shen, Worrell and Patel, 2010) that provide (information for deriving) substitution factors were identified. Based on these two studies, using wood to produce textile fibres may to lead to a substitution effect of 2.8 kg C/kg C (with 95 percent of the values ranging between 2.5 kg C/kg C and 3.1 kg C/kg C), thereby providing the largest substitution benefits across all product types considered. The existing two studies indicate that the production of wood-based, man-made fibres such as viscose, lyocell and modal results in lower levels of CO_2 emissions than the production of cotton or petroleum-based fibres. Shen, Worrell and Patel (2010) also highlight that the production technology and resource base used could have a significant effect on the estimated substitution effects. For example, an integrated textile fibres and pulp plant using modern technology and factory biomass for process energy was found to give lower levels of GHG emissions compared to conventional textile production technology using market pulp instead of integrated own pulp.

Substitution factors for other product categories

Other product categories, such as wood-based chemicals, packaging and furniture generally result in moderate substitution benefits with average factors ranging between 1.0 kg C/kg C and 1.5 kg C/kg C wood product. However, these results are based on only a few studies and are limited to just a few product comparisons, which makes it difficult to generalize about all chemical products. Similarly, only one study exists comparing the life cycle emissions of a printed magazine and an electronic tablet version. The study highlights that the substitution factor may be a positive or negative value, strongly depending on the number of readers for the tablet edition, number of readers per copy for the print edition, file size, and degree of use of the tablet for other purposes (Achachlouei and Moberg, 2015).

The reported substitution benefits mainly relate to existing products, but the development of the bioeconomy is generally considered to provide new possibilities for transforming biological resources into new bio-based products that can replace emissions-intensive products such as construction materials, textiles, chemicals and plastics (Sillanpää and Ncibi, 2017). However, for emerging forest or wood-based products, (climate-related) impacts are not well understood. For example, few LCA studies exist for CLT used in construction, and the understanding of substitution benefits for other engineered wood products, as well as other novel or emerging wood products, is far less well developed (Sahoo *et al.*, 2019).

5.2.3 Regional and market level climate-related substitution effects

Substitution effects are typically reported in the literature at the level of individual products. However, to get an overview of substitution effects at the level of markets, regions, or countries, it is important to consider all types of products being produced, as well as their share in the total product mix (Bösch *et al.*, 2019; Braun *et al.*, 2016; Geng *et al.*, 2019; Geng, Chen and Yang, 2019; Knauf *et al.*, 2015; Matsumoto *et al.*, 2016; Smyth *et al.*, 2017; Soimakallio *et al.*, 2016; Suter, Steubing and Hellweg, 2017). In contrast to studies reporting on product-level substitution effects, there are relatively few studies that report (weighted) substitution factors for forest product markets, regions or countries (see Table 5.1) and it is difficult to draw firm conclusions. A possible reason for the few studies on this topic is limited information on end uses of wood and the difficulty in determining which materials are substituted. The studies generally highlight that substitution effects are an important factor to consider when devising climate change mitigation strategies for forest management and forestry.

Table 5.1. Overview of weighted substitution effects at the level of forest product markets, regions and countries

Country, region or market considered	Weighted substitution effect	Summary of the study	Reference
Finnish forest industry	1.13 kg C/kg C	Based on product-level substitution factors from the literature, the study estimated a national substitution factor based on domestic wood-based products and fuels produced by the Finnish forest industry. The study also shows that if the wood harvest was increased by 17–33 percent in Finland compared to the baseline scenario, a substitution factor of 2.0 to 2.4 kg C/kg C would be needed to compensate for decreased carbon storage in forests.	Seppälä *et al.* (2019)
Canada, built sector	0.54 kg C/kg C for sawnwood and 0.45 kg C/kg C for panels	The study determined displacement factors for wood substitution in the built environment and bioenergy at the national level in Canada. For solid wood products, the study compiled a basket of end-use products and determined the reduction in emissions for two functionally equivalent products. Avoided emissions for the basket of end-use products were weighted by Canadian consumption statistics to reflect national wood uses. The results demonstrated that the average displacement factors were 0.54 kg C/kg C displaced per tonnes C of used sawnwood and 0.45 kg C/kg C for panels.	Smyth *et al.* (2017)
Switzerland	0.55 kg C/kg C of wood used	The study conducted a material flow analysis of wood use in Switzerland. Production data for wood products were obtained from annual statistics and reports and were combined with information obtained from life cycle assessments. The study considered 52 processes that produce 40 wood-based products covering the different sectors of the wood market up to semi-finished products.	Suter, Steubing and Hellweg (2017)

Country, region or market considered	**Weighted substitution effect**	**Summary of the study**	**Reference**
Construction and furniture sectors in China	3.48 kg C/kg C (construction); 1.36 kg C/kg C (furniture)	The study estimated product-specific substitution factors for China and weighted these by their end use. The weighted average substitution factors for substituting wood-based products for non-wood materials in construction and furniture production in China were estimated to be 3.48 kg C/kg C and 1.36 kg for wood-based products substitution when these two sectors were combined.	Geng, Chen and Yang (2019)
Furniture sector in China	1.46 kg C/kg C	The study quantified substitution benefits of wood furniture in China via national-scale mitigation analyses. The authors selected a basket of representative furniture and estimated the emission reduction for two functionally equivalent products, which differ in wood intensity. The emissions avoided in each type of product were weighted by its share of the furniture market. The overall displacement factor for the wood material was 2.67 kg CO_2 e/kg or 1.46 kg C/kg C.	Geng *et al.* (2019)
North Rhine-Westphalia/Germany	1.5 kg C/kg C	The study defined 16 product areas for which single substitution factors were determined. The substitution factors were combined with quantitative information on wood use in Germany to calculate a volume-weighted substitution factor.	Knauf *et al.* (2015)

5.2.4 Variability and uncertainties of climate-related substitution factors

Estimating and generalizing the substitution benefits of wood products are not straightforward and there is a significant variability in the results (Gustavsson and Sathre, 2006; Leskinen *et al.*, 2018; Sathre and O'Connor, 2010). In general, substitution factors are often estimated for a particular wood product and compared to a certain functionally equivalent, non-wood alternative. Most studies indicate that using wood or wood-based products often results in lower emissions during the forest product production stage (i.e. wood processing and manufacturing) when compared to most other products. Assumptions on the end-of-life practices have important effects on the comparison of emissions between a wood product and its non-wood equivalent (Sandin, Peters and Svanström, 2014). At the end-of-life stage, wood-based products can be recycled or used for energy production, while metals and alloys can be recycled, which affects the end-of-life stage substitution benefits for wood products.

In contrast, cement, concrete, ceramics and stone have limited end-of-life utility, leading to higher substitution factors for wood products (Leskinen *et al.*, 2018). One additional reason for increased variability in substitution factors is the difference between the types of energy production systems in different countries and regions. For example, the estimated substitution effect can substantially change based on the assumed type of energy to be replaced (Cherubini *et al.*, 2009; Cherubini and Strømman, 2011; Gustavsson and Sathre, 2006).

An important reason for variability is thus that substitution values are based on many different product types, the non-wood materials that are substituted, production technologies, number of life cycle stages considered, and end-of-life management practices. Other important factors contributing to the variability relate to data and other methodological choices such as system boundaries, the metric used to indicate climate impacts, and the time horizons considered (Leskinen *et al.*, 2018; Rosa, Pizzol and Schmidt, 2018; Sahoo *et al.*, 2019). One difficulty encountered when reviewing literature is the lack of detailed information on how the emissions from wood products and their substitutes are modelled. Often crucial information like the allocation procedure used is missing and, in several cases, the studies are not transparent concerning the assumptions made. All these factors make it difficult to generalize substitution effects provided by wood-based products. Nevertheless, there is strong evidence that the production, use and end-of-life of wood-based products provide climate benefits at the level of forest products. As highlighted by Leskinen *et al.* (2018), the variation in the results could be reduced by improving the quantity and quality of data available in the future, and by following a harmonized, agreed-upon methodology to derive substitution factors.

It is also important to note that comparisons of emissions from wood-based products and their non-wood equivalents exclude the carbon balance in forest ecosystems. To get a full picture on climate impacts, it is also important to consider the carbon balances of forest biomass and soil, as well as carbon stored in wood products.

5.2.5 Gaps in the understanding of substitution effects

Based on a review of existing literature, a number of knowledge gaps can be identified in the current understanding of substitution effects by forest products:

- Most studies in the literature focus on construction and significantly less information exists for other product types. The use of wood is expected to increase in the future, for example in textiles, nanocellulose, packaging, chemicals, biofuels and a large variety of downstream niche markets (Hurmekoski *et al.*, 2018; Lettner *et al.*, 2018) Few LCA studies are generally available for these products (Sahoo *et al.*, 2019) and their substitution effects with regard to climate and other environmental impacts are not well understood.
- Due to their large volume, printing and writing paper as well as packaging paper could have a significant impact on the overall substitution impact of industrial wood usage, yet there is insufficient information available on substitution factors to assess the substitution impact of these product categories (Leskinen *et al.*, 2018). Graphic papers (printing and writing papers and newsprint) are increasingly being substituted by electronic media, yet there are not many studies quantifying the substitution impact.
- The studies reporting on substitution effects typically rely on current product design, technologies and energy supply. While the past and current situation is well known, future product design and changes in technologies and energy supply are difficult to predict and depend on many factors, including future policy instruments. It is thus challenging to estimate how these future changes will impact substitution benefits (Harmon, 2019; Leskinen *et al.*, 2018).
- Most of the studies from which substitution factors could be derived focus on North America and the Nordic countries in Europe, and substitution effects by wood products from many other areas of the world are not well understood, despite their relative importance in the global wood markets. Improved understanding is needed on product substitution effects in other contexts.
- Substitution by wood-based products can provide climate benefits at the level of forest products. However, the production of wood products can also reduce the carbon balances of forest ecosystems. It is not clear whether the decrease in carbon storage in forests would be offset by gains in carbon storage in wood products, and through product substitution effects (e.g. Seppälä *et al.*, 2019; Soimakallio *et al.*, 2016). The net balance will critically depend, among many other factors, on the forest ecosystem considered, the wood products produced, the materials replaced, the production technologies and efficiencies applied, and the time considered.

5.3 Other environmental substitution effects

Wood-based products generally provide climate benefits when compared to functionally equivalent products made from other, non-renewable materials. This is because wood-based materials are typically associated with lower CO_2 emissions during their production and end use. However, using wood-based products instead of products made from other materials will have other impacts.

Existing LCA studies on forest products indicate that there are climate-related impacts in the processing, manufacturing, use and disposal of products. In addition, there are impacts related to eutrophication, acidification, photochemical oxidant formation and human toxicity, but understanding of these impacts is still limited (Klein *et al.*, 2015; Mäkelä, 2017). While reviews exist on the environmental impacts of wood products (Sahoo *et al.*, 2019), no studies systematically analyzing non-climate substitution effects for wood-based products were identified. Weiss *et al.* (2012) conducted a systematic review of the existing LCA literature on bio-based materials. Their review included products made from wood, but also other biomass from terrestrial and marine plants, residues and waste.

In their review, Weiss *et al.* (2012) focused on climate change impacts, as well as non-renewable energy use, eutrophication, acidification, stratospheric ozone depletion and photochemical ozone formation. The authors found that bio-based products generally exerted lower climate change impacts (Figure 5.4) and that bio-based products required less energy. However, the manufacturing of bio-based products might exert higher environmental impacts than their conventional fossil-based or mineral-based counterparts in the categories of eutrophication and stratospheric ozone depletion. The authors did not find conclusive results with regard to acidification and photochemical ozone formation.

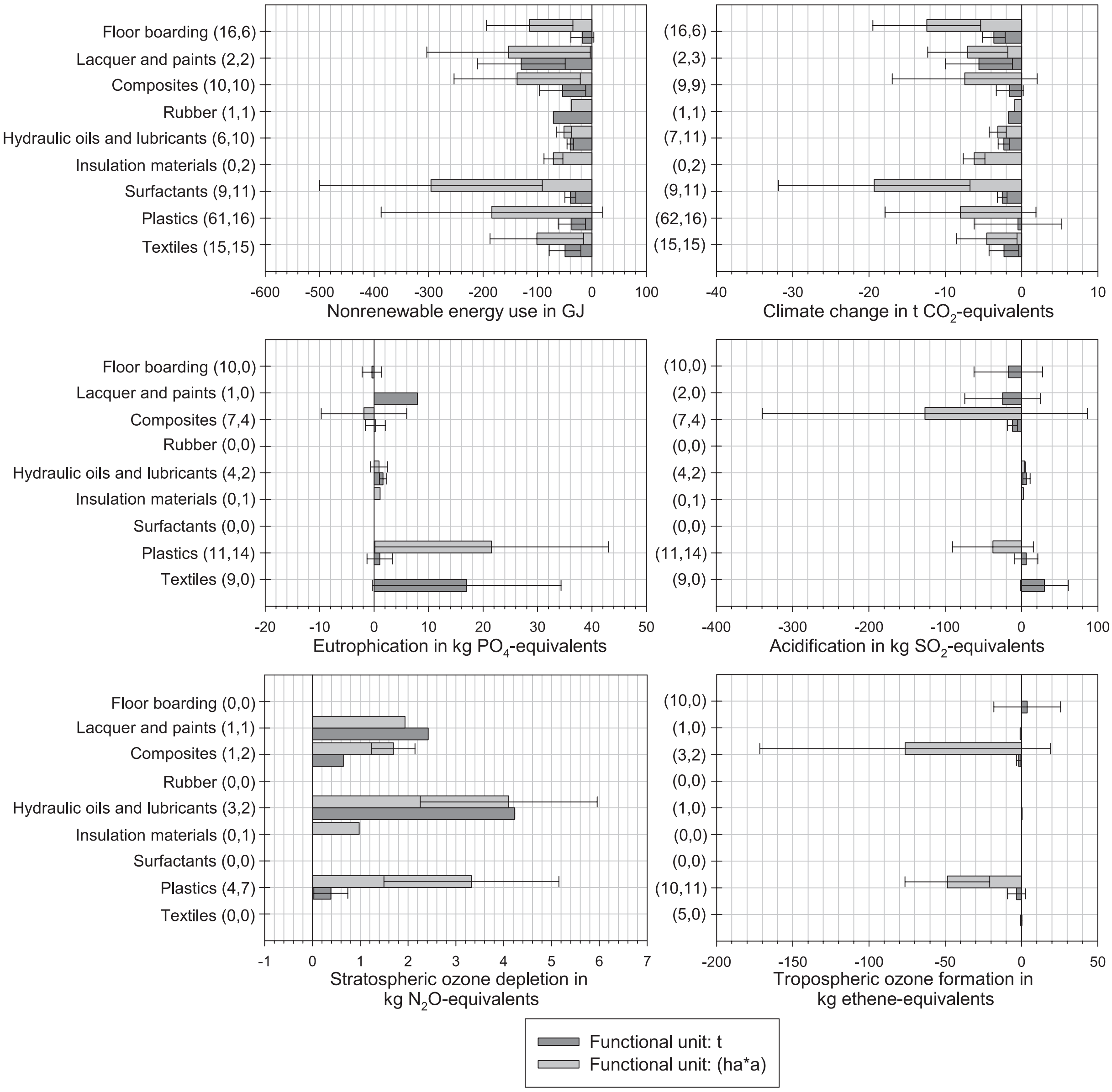


Figure 5.5. Average product-specific environmental impacts of bio-based materials in comparison to conventional materials

Note: The relative environmental impacts of bio-based materials are the difference between environmental impacts of bio-based materials and conventional materials. The relative environmental impact is shown per metric tonne of product and per hectare of agricultural land and year (ha∗a). Uncertainty intervals represent the standard deviation of data. Numbers in parentheses indicate the sample size for each of the functional units respectively.
Source: Weiss *et al.*, 2012.

The authors found that most studies focused on bio-based materials of European origin. Similar to the review presented in section 5.2 on climate substitution effects, Weiss *et al.* (2012) highlighted the differences in assumptions and methodological choices and the lack of transparency in the methods and results presented in the literature.

As indicated above, many LCA studies typically focus on a few impact environmental categories, although there are obviously other impacts. Biodiversity is an important impact category, but biodiversity is still poorly addressed in LCA studies (Crenna *et al.*, 2020; Winter *et al.*, 2017) and no studies were found to assess substitution effects on biodiversity using an LCA analysis.

5.4 Substitution of forest products for high greenhouse gas-based products and the Sustainable Development Goals

The long history of sustainability thinking in forestry is relevant when we consider SDGs. While the aim is to achieve all goals, there are likely to be synergies and trade-offs between SDGs (Baumgartner, 2019; Pradhan *et al.*, 2017; van Zanten and van Tulder, 2020). A recent review of scientific literature on how agricultural (including forestry), industrial and manufacturing activities affect SDGs (van Zanten and van Tulder, 2020) found that studies on economic activities predominantly reported negative impacts of those activities on environmental development. Economic activities are generally considered to positively affect SDGs 9 (Industrialization, Infrastructure and innovation) and 8 (Economic Productivity), but SDGs 3 (Human Health), 13 (Climate Action), 14 and 15 (Aquatic and Terrestrial Ecosystems) are generally negatively affected by economic activities (van Zanten and van Tulder, 2020). While the findings relate to all economic activities, synergies and trade-offs between SDGs also exist for the forest sector. Forest sector activities are closely linked to SDGs 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 12 (Responsible Consumption and production), 13 (Climate Action) and 15 (Life on Land), as well as other SDGs (Baumgartner, 2019; WBCSD, 2020).

Among the 17 SDGs set by the United Nations (2015), substitution by wood-based products could contribute specifically to SDGs 12 (Responsible Consumption and Production), 13 (Climate Action) and 15 (Life on Land). In addition to the SDGs, six Global Forest Goals have been set to contribute to the progress on the SDGs (United Nations Economic and Social Council, 2017). Among the six Global Forest Goals, substitution can play a role in contributing to Global Forest Goal 2 (Enhance forest-based economic, social, and environmental benefits, including by improving the livelihoods of forest-dependent people).

To understand how substitution could contribute to meeting some of the targets set by the United Nations (2015), we focused on examining different key factors likely to determine the contribution of substitution to the three selected SDGs and Global Forest Goal 2. To this end, the most relevant indicators under the SDGs were identified and are described below: these provide reference points for understanding and measuring progress toward implementing the SDGs.

5.4.1 SDG 12: Responsible consumption and production

For over a century, society's economic and social progress has been associated with the exploitation of natural resources. However, the extraction and use of natural resources have mostly occurred in an unsustainable manner, creating dependency on fossil-based and GHG-intensive materials, and resulting in environmental degradation. According to the United Nations (2015), sustainable consumption and production should be more efficient, by doing more and better with less. SDG12 aims to disconnect economic growth from environmental degradation by increasing resource efficiency, reducing degradation and pollution along the whole life cycle, and promoting sustainable lifestyles (UNEP, 2010).

Material Footprint

Material Footprint (MF; SDG indicator 12.2.1) refers to the attribution of global material extraction to the domestic final demand of a country. The total MF is the sum of the material footprint for biomass, fossil fuels, metal ores and non-metal ores (UN, undated). The indicator is measured in tonnes. Substitution could affect the material footprint as follows:

- Wood is generally less dense (approximately 550 kg/m^3) than other materials (e.g. steel 7 850 kg/m^3, bricks 480–2 405 kg/m^3 (Engineering ToolBox, 2004, 2011), while maintaining important structural properties. A brick and block building weighing approximately 80 million tonnes could be 5.3 times heavier than a timber-frame building (Benjamin, 2016). Substitution could reduce the material footprint.
- Production losses are approximately 4–9 percent in steel production, but losses can be recycled almost entirely as scrap on the same production line (Bowyer *et al.*, 2015; Kotas, 2011). In wood processing, losses are generally larger (FAO, ITTO and United Nations, 2020), although production residues are used as different by-products. In the case of production of steel and wood products, substitution could increase the need for material extraction and thus have an increasing effect on MF due to differences in production efficiency.
- The amount of fossil fuel inputs in production and extraction processes affects the MF. Wood harvesting can be done using light machinery or even chainsaws, whereas the extraction of minerals generally requires heavy machinery and comparatively higher fossil fuel inputs. Steel and concrete manufacturing processes require more energy than those of wood (Adhikari and Ozarska, 2018). Modern pulp mills can meet all their energy requirements from internal processing residues and generate an energy surplus (Shen, Worrell and Patel, 2010), whereas the energy inputs for steel and concrete are external. Substitution could thus lead to less demand for fossil fuel inputs in production and extraction processes, thus lowering the MF.
- Another question linked to MF relates to global trade, which requires fossil fuel inputs for transport (e.g. for cargo vessels). Increased net global trade would thus lead to a larger MF and less trade to a smaller MF. Wood as a natural resource is available locally in most world regions, while some metal/non-metal ores are only found in some parts of the world, requiring trade and transport to other world regions. Substitution could thus result in less net global trade, requiring fewer fossil fuels which would lower the MF.

In sum, the impact of substitution on MF is conditional on several factors, such as different material properties and applications, production processes and efficiencies, and trade implications. Given this complexity, it is not feasible to try to summarize any overall, aggregate impact. Instead, the impact of substitution on the indicator should be examined on a case-by-case basis.

Hazardous waste

Hazardous waste (SDG indicator 12.4.2) is waste with properties that make it hazardous or capable of having a harmful effect on human health or the environment. Hazardous waste is generated from many sources, ranging from industrial manufacturing processes to domestic items such as batteries, and may come in many forms, including liquids, solids, gases and sludge. This waste can be discarded in commercial products like cleaning fluids or pesticides, or in by-products from manufacturing processes. Treatment refers to recycling, incineration, incineration with energy recovery, landfilling, and other processes. This indicator is measured in tonnes. Substitution could affect hazardous waste as follows:

- Wood by itself is non-hazardous, but hazardous substances can be used for manufacturing forest products, or for modifying the properties of wood products. For example, engineered wood products can be glued together with adhesives that are considered hazardous (Sathre and González-García, 2014). New technologies could reduce (e.g. when producing textile fibres from wood pulp) or even dispense with (e.g. heat treatment) the use of harsh chemicals. For some products, substitution (e.g. cotton replaced by wood-based fibres) could also reduce the need for fertilizers, pesticides and irrigation. Similarly, the use of some chemicals results in wood being considered contaminated, which can be avoided by using non-contaminating substances (Sathre and González-García, 2014). The impact of substitution on hazardous waste depends on the wood and non-wood products being considered, as well as their production technologies.
- At the end-of-life stage, substitution could result in changes in the amounts of hazardous waste that needs processing. Considering the processing options (e.g. recycling, incineration, incineration with energy recovery or landfilling), hazardous wood waste can be dealt with, for example, by processing it into fibreboards or other similar wood products or incinerating it to recover energy in a safe way in specialized plants (Block *et al.*, 2015). Nonetheless, it is difficult to come to a general conclusion on whether increased amounts of hazardous wood – a potential result of substitution – would require more processing than other hazardous materials; this will depend on local legislation, which specifies what is considered hazardous waste.

As with the previous indicator, it is difficult to draw a conclusion on an overall impact of substitution on this indicator, since the outcome could depend on several case-specific factors and conditions.

Recycling rate

Recycling can be defined as "*any reprocessing of waste material […] that diverts it from the waste stream, except reuse as fuel. Both reprocessing as the same type of product and for different purposes should be included. Recycling within industrial plants i.e. at the place of generation should be excluded*" (UN, undated). Recycling includes co-digestion/anaerobic digestion and the composting/aerobic process, but excludes controlled combustion (incineration) and land application. National recycling rates (SDG indicator 12.5.1, tonnes of material recycled) are calculated by adding together the material recycled and the material exported for recycling, then subtracting the material imported for recycling. That result is then divided by the total waste generated.

The recycling rate is intrinsically related to the end-of-life stage. The effect of substitution on the indicator depends on whether substitution enables higher recycling rates. In other words, if wood is recycled proportionally more than other materials are, then substitution could lead to a higher recycling rate. A study that examined the recycling of 60 different metals found that only 18 metals had a recycling rate of 50 percent or higher (Graedel *et al.*, 2011), while a study on concrete recycling in the United States of America indicated a recycling rate of nearly 75 percent (Jin and Chen, 2019). Wood products have significant potential for recycling, but that potential remains untapped for several product categories and varies around the world. The global recycling rate of all paper and paperboard between 2015 and 2019 was 46 percent (FAOSTAT, 2020), but recycling rates in other wood product categories are not comprehensively recorded. If substitution is to contribute to higher recycling rates, there is no doubt a need to strengthen the cascading use of wood products i.e. reuse/recycle them before utilizing them for energy recovery.

5.4.2 SDG 13: Climate action

The increase in global temperature, the associated climate change impacts and environmental degradation are a threat to ecosystems and the survival of many communities that depend on natural resources. SDG 13 focuses on reducing GHG emissions and adapting to the adverse impacts of climate change (United Nations, 2015).

Total GHG emissions (SDG indicator 13.2.2) refers to the process by which pollutants are emitted to the atmosphere and contribute to climate change. The indicator covers the emissions of carbon dioxide, methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons, sulphur hexafluoride and nitrogen trifluoride (expressed in units of CO_2 equivalent per year). As highlighted in section 5.2, there is strong evidence at the product level that wood products are associated with lower GHG emissions in their production, use and disposal over their lifetime compared to products made from emission-intensive and non-renewable materials (Geng *et al.*, 2017; Leskinen *et al.*, 2018; Sathre and O’Connor, 2010). Few examples exist of their total potential to reduce GHG emissions, but a recent study on the global mitigation potential of mid-rise urban buildings designed with engineered wood products estimated a mitigation potential for material substitution at 0–1.2 Gt CO_2e per year (Churkina *et al.*, 2020; Oliver *et al.*, 2014). For comparison, improved forest management practices can potentially contribute to climate change mitigation by 0.4–2.1 Gt CO_2e per year and forest degradation avoided has been estimated to represent a global climate change mitigation potential of 1–2.2 Gt CO_2e per year (Roe *et al.*, 2019).

5.4.3 SDG 15: Life on land

Environmental degradation, caused by the unsustainable exploitation of natural resources and potentialized by the adverse effects of climate change, refers to desertification, land degradation, freshwater scarcity and biodiversity loss, among other effects. SDG 15 focuses on the sustainable use, management and conservation of all terrestrial ecosystems, including forests.

Halting deforestation and improved, sustainable forest management practices can also help mitigate impacts on biodiversity. Chaudhary *et al.* (2016) reviewed 287 published studies containing 1 008 comparisons of species richness in managed and unmanaged forests, and found that all types of forest management affect forest biodiversity, but that impacts varied substantially between forest management types. In terms of local species richness loss, selection and retention systems and reduced-impact logging have limited impacts on biodiversity, while timber plantations have a strong impact (on average 40 percent reduction in local species richness compared to unmanaged, natural forests), followed by clear-cutting (22 percent reduction) and conventional selective logging (13 percent reduction) (Chaudhary *et al.*, 2016). The enhanced use of wood will thus be associated with biodiversity impacts, but the impact will depend on how forest management is conducted and what reference situation is considered.

Forest area as a proportion of total land area

Forest area as a proportion of total land area (SDG indicator 15.1.1) is measured as a percentage. It could be assumed that substitution would lead to increases in forest area, since a rise in wood demand could require reforestation, afforestation and improved forest management to ensure sufficient feedstock availability. However, there is also the risk that expanding the forest resource base could fail to keep up with rising wood demand, which could cause the forest area to decrease or be degraded (Payn *et al.*, 2015).

Progress towards sustainable forest management

This indicator (SDG indicator 15.2.1) is composed of five sub-indicators that measure progress towards all dimensions of sustainable forest management: 1. Forest area annual net change rate (measured as a percentage of hectares); 2. Above-ground biomass stock in forest (measured in tonnes per hectare); 3. Proportion of forest area located within legally established protected areas (measured as a percentage of hectares); 4. Proportion of forest area under a long-term forest management plan (measured as a percentage of hectares); 5. Forest area under an independently verified forest management certification scheme (measured in hectares).

Sub-indicators 1 and 2 are linked to indicator 15.1.1, i.e. substitution could have a positive effect, but there is also the risk of a negative effect. In other words, it depends on whether increasing wood demand as a result of substitution in the bioeconomy would, at the minimum, be offset by reforestation and afforestation efforts and appropriate forest management practices. Regarding sub-indicator 3, it might be unrealistic to expect substitution to contribute positively, since legally established protected areas are not intended for production. However, the contribution might not be negative: it could be neutral. For sub-indicator 4, the need for increasing forest production (as induced by substitution) could drive the design and implementation of sustainable forest management plans to ensure sustained feedstock yields and safeguard various social, economic and environmental forest values. The development of new, high-value-added products could attract investments with potential to stimulate and improve forest management. However, substitution could also have the opposite effect if new forest production areas are rapidly established to satisfy growing market demand without due consideration of sustainability issues. In particular, this could be the case in countries with comparatively weaker policy and legal frameworks and rule of law. Complementary to sub-indicator 4, progress with sub-indicator 5 could be enhanced where forest managers are willing to demonstrate compliance with sustainable forest management and consumers' demand for certified products. Alternatively, substitution could hinder progress with this sub-indicator in line with the "negative" scenario described in sub-indicator 4. On balance, a positive contribution to this indicator could be expected, thanks to increased demand for and valorization of wood in the bioeconomy.

Proportion of land that is degraded over total land area

The proportion of land that is degraded (SDG indicator 15.3.1) consists of three sub-indicators: 1. Trends in Land Cover; 2. Land Productivity; 3. Carbon Stocks. In the context of forests, these aim to capture the overall extent and health of the forest ecosystem. Linked to indicator 15.2.1, tree planting could contribute to restoration of degraded land. However, a high demand for forest products and poor, unsustainable forest management practices could cause land degradation. In some circumstances, replacing natural forests with planted forests, for example, could cause a negative effect on the overall indicator due to decreases in biomass and carbon stock (Chen, Liang and Wang, 2016).

5.4.4 Global Forest Goal 2: Economic, social and environmental benefits from forests

The six Global Forest Goals and 26 associated targets were developed as part of the "UN strategic plan for forests 2017–2030". They build on and aim to contribute to progress on the SDGs, the Aichi Biodiversity Targets and the Paris Agreement on climate change. The six goals cover a wide variety of thematic areas linked with economic, environmental and social sustainability. Global Forest Goal 2 aims to enhance forest-based economic, social and environmental benefits, including by improving the livelihoods of forest-dependent people. Substitution could contribute to Global Forest Goal 2, as shown in Table 5.2.

Table 5.2. Contribution of substitution to Global Forest Goal 2

Target	Contribution by substitution
Target 2.1 Extreme poverty for all forest-dependent people is eradicated	As a result of increased use of the forest resource, forest-dependent people living in extreme poverty could benefit from economic opportunities and new livelihood options arising from the utilization of wood, for example through the harvesting and processing of timber in agroforestry practices (Miller, Mansourian and Wildburger, 2020). However, such scenarios would need to follow good governance principles to ensure forest-dependent people benefit equitably.
Target 2.2 Increase the access of small-scale forest enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets	The emergence of new forest products due to substitution in the bioeconomy can offer new market opportunities to small-scale forest enterprises, for example, by supplying feedstock.
Target 2.3 The contribution of forests and trees to food security is significantly increased	A higher valorization of trees induced by substitution could provide enhanced livelihoods to some forest communities, thus enabling increased food security.
Target 2.4 The contribution of the forest industry, other forest-based enterprises, and forest ecosystem services to social, economic and environmental development, among others, is significantly increased	Through (a wider) economic utilization of the forest resource and following sustainable forest management, it is possible to contribute to sustainable development in its three dimensions (social, economic, environmental) (Katila *et al.*, 2019; Tegegne *et al.*, 2019).
Target 2.5 The contribution of all types of forests to biodiversity conservation and climate change mitigation and adaptation is enhanced, taking into account the mandates and ongoing work of relevant conventions and instruments	If an increase in forest area induced by substitution leads to planted forests replacing natural forests, there is a risk of biodiversity loss. Substitution could contribute to climate change mitigation through tree planting and carbon storage in harvested wood products. Increasing forest areas could function as a safety net to forest-dependent people against adverse climate change impacts through the utilization of different forest ecosystem services (FAO, 2014).

5.5 Summary

There is strong evidence at the product level that wood products are associated with fewer GHG emissions in their production, use and disposal over their lifetime compared to products made from emission-intensive and non-renewable materials. However, there is still limited understanding of the substitution effects at the level of markets, countries or global regions, presumably due to limited information on the end uses of wood and the difficulty in determining which materials are substituted (Leskinen *et al.*, 2018). The reviewed product-level substitution factors have substantial variability and uncertainty, which can be explained by differences in assumptions, data and methods. Substitution factors reported in or derived from the international literature are context specific and generalizations are not therefore straightforward. For example, substitution effects depend on the type of wood product being considered, the type of non-wood product that it substitutes, the different operating life, as well as the end-of-life management of wood and non-wood products. The overall substitution effects also depend on the share of different forest products in the total product mix of a sector or country (Leskinen *et al.*, 2018).

Besides climate impacts, substitution can also have other environmental impacts. Understanding of these impacts is still limited, and they need to be compared with the impacts that occur during the manufacturing, use and disposal of the non-wood products that they substitute (Churkina *et al.*, 2020; Weiss *et al.*, 2012). Substitution also contributes to sustainable development. The contribution of substitution to SDG 12 (Responsible Consumption and Production) appears conditional on various case-specific factors and could be positive, negative or neutral. Progress toward implementing SDG 13 (Climate Action) and 15 (Life on Land) could more clearly benefit from substitution.

Take-home messages

- Wood and wood-based products generally provide climate benefits due to lower process-based emissions when compared to non-wood products.
- The benefits for climate change provided by substitution with wood products need to be considered together with carbon storage in forest ecosystems and wood products.
- To improve understanding of the benefits provided by substitution with wood products at the level of markets or countries, we need to address knowledge gaps related to current and future production technologies, product mixes and the energy supply of both existing and emerging forest products (e.g. paper, textiles, packaging, chemicals).
- It is important to consider all the (environmental) impacts related to substitution to find synergies and minimize trade-offs.

6 Future demand and supply dynamics of forest products

Global supply and demand for wood products is dynamic, shifting in volume and between regions. It is influenced by various drivers, including the availability of wood, product and technological developments, product prices, consumer preferences and behaviour, as well as an expanding global middle class and population growth more generally. Various policy and regulatory developments, such as those relating to responsible-sourcing strategies, carbon programmes, renewable energy development and green building standards, also affect production and trade (UNECE/FAO, 2019). The effect of some of these drivers on future supply and demand for forest products is fairly well understood, but structural changes are often more difficult to consider. Examples of these structural changes are substitution due to new technologies or policy-driven changes, such as digital media replacing print media, or climate policies causing the substitution of fossil-based products and energy. This chapter outlines recent understanding of the future global supply and demand dynamics of forest products and the potential impact that increased substitution may have on these dynamics.

6.1 Forest sector outlook

Worldwide wood consumption is steadily growing. Global production of roundwood (the sum of industrial roundwood and fuelwood) increased from 2.5 billion cubic metres in 1961 to 4 billion cubic metres in 2019 (FAOSTAT, 2020). In the bioeconomy context, forest production systems will face increasing pressure due to multiple demands for biomass for energy and material uses. However, there are also factors that may alter or revert these trends. These factors could be increased productivity in wood production, the use of forest residues or by-product material streams instead of roundwood, improved recycling of wood products, declining graphic paper demand, possibilities for more efficient fuelwood consumption, or using alternatives to fuelwood for energy (about half of the world roundwood production is fuelwood) (Hetemäki, Palahí and Nasi, 2020; Hurmekoski *et al.*, 2018). The overall outcome of these different factors is unclear and there is a lack of systematic and up-to-date outlook studies providing a sound basis for conclusions on world roundwood consumption in the decades to come (Hetemäki and Hurmekoski, 2016; Hetemäki, Palahí and Nasi, 2020).

Several studies have been conducted to assess future supply and demand for forest products based on historic trends as well as plausible future development scenarios. Johnston and Radeloff (2019) applied the Global Forest Products Model to project the production of major wood products up until 2065, focusing on traditional wood products and not considering structural changes taking place in the sector. This model for the global forest sector considers both the demand for products and the supply of raw materials to estimate future production, consumption and trade. The model was applied using the Shared Socioeconomic Pathways (SSPs), which are an internationally established set of five scenarios[2] developed in the context of IPCC assess-

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[2] The five pathways include: SSP1: Sustainability (Taking the Green Road); SSP2: Middle of the Road; SSP3: Regional Rivalry (A Rocky Road); SSP4: Inequality (A Road Divided); and SSP5: Fossil-fuelled Development (Taking the Highway)

ments, and they contain projected socioeconomic global changes up to 2100 (O'Neill *et al.*, 2017; Riahi *et al.*, 2017).

Based on these scenarios, Johnston and Radeloff (2019) projected the global production for multiple forest product categories, including industrial roundwood, sawnwood, panels, wood pulp, and paper and paperboard (see Figure 6.1 to Figure 6.6, respectively). Across all product categories, most distinct is the projected rise of industrial roundwood production, which is estimated to increase by 19–53 percent by 2065 compared to 2015 levels. For other product categories, Johnston and Radeloff (2019) estimated sawnwood production to reach 526–606 million cubic metres by 2065, panels 552–894 million cubic metres, and wood pulp and paper and paperboard 135–184 million tonnes and 546–712 million tonnes, respectively. For comparison, Jonsson *et al.* (2018) estimated global sawnwood production to reach 495 million cubic metres by 2030 and the production of plywood, particle board and fibreboard to reach around 320–350 million cubic metres by 2030. For the product categories of newsprint, printing and writing paper, packaging, and household and sanitary papers, Jonsson *et al.* (2018) estimated the global production level in 2030 to be around 425–440 million tonnes, depending on the scenario. This does not reach the production levels in the lowest scenarios modelled by Johnston and Radeloff (2019), but the coverage of paper and paperboard product categories may also be less comprehensive when compared to that of Johnston and Radeloff (2019).

Long-term projections of forest product supply and demand suffer from several uncertainties and knowledge gaps. One knowledge gap on future forest product markets – and the raw material that will be required – concerns the evolution of new wood-based products and the role of investments that would enable such sector diversification. Many new wood-based products are still experimental, and it is uncertain how product development will materialize and how markets will take up these innovations. What will enable or inhibit the emergence of new wood-based products is linked to investments both in capital and in research (Lovrić *et al.* (2020); see also Chapter 4). Hence, how investments will unfold will greatly impact the future role and development of wood products in the bioeconomy.

Another knowledge gap relates to future demand for bioenergy as well as its increased substitution for other energy sources. These could potentially compete with the wood raw material requirements for traditional wood products (Hänninen *et al.*, 2018). For example, forest bioenergy currently often uses residues and by-products from harvesting operations and sawnwood milling as feedstock. However, the pulp and paper industry uses the same sources as feedstock and this industry is expected to grow significantly due to the rising popularity of e-commerce, for which wrapping and packaging materials made of wood fibre are needed (Hurmekoski *et al.*, 2018).

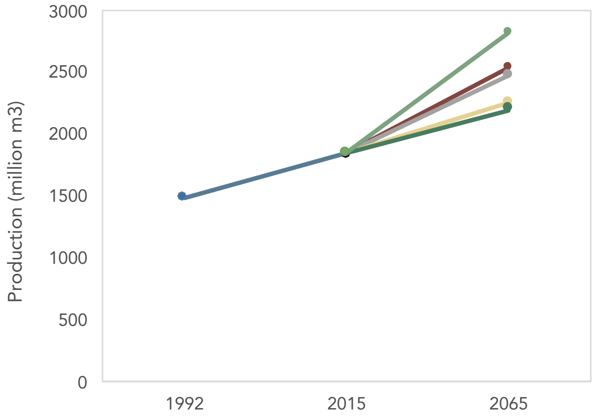

Figure 6.1. Global industrial roundwood production

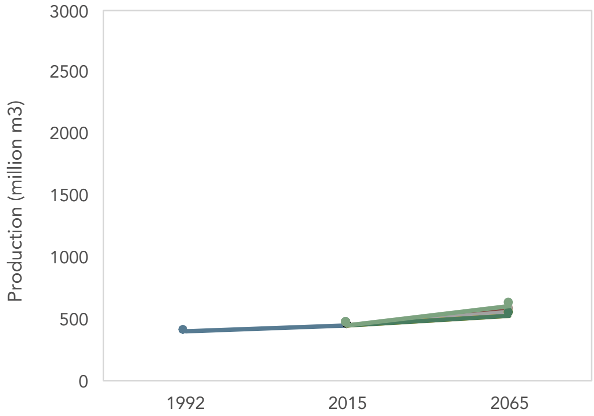

Figure 6.2. Global sawnwood production

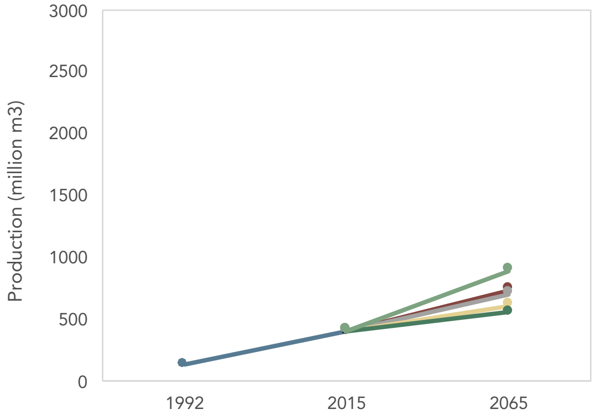

Figure 6.3. Global wood panel production

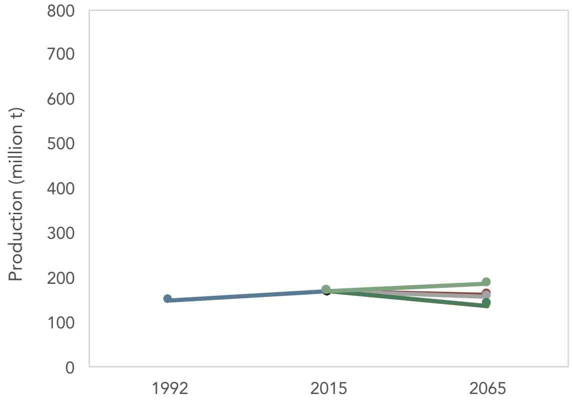

Figure 6.4. Global wood pulp production

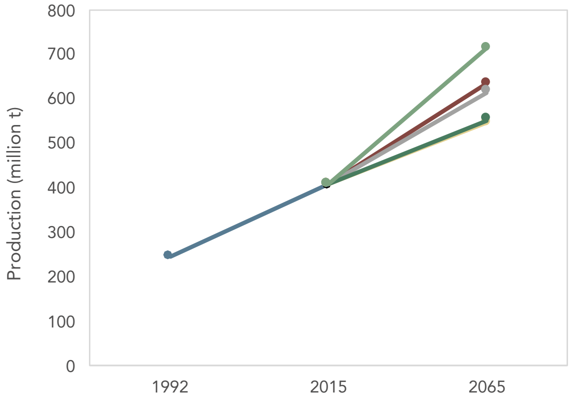

Figure 6.5. Global paper and paperboard production

● Historical ● SSP1 ● SSP2 ● SSP3 ● SSP4 ● SSP5

Source: Johnston and Radeloff (2019)

6.2 Product substitution and future supply and demand dynamics

A key question is if and how substitution by wood products would result in additional roundwood demand. As outlined in section 5.2.3, there is still limited understanding on substitution effects at market, country or global level. Few studies have been conducted to investigate the amount of wood that would be needed to implement substitution at large scale. An overview is given in Table 6.1.

Table 6.1. Overview of studies estimating the effects of product substitution on future supply and demand dynamics

Case study	Case study description	Avoided emissions	Additional roundwood demand
Global coniferous sawnwood production (Leskinen *et al.*, 2018)	Production of sawnwood increases at an annual rate of 1.8 percent to 2030. Around 50 percent of coniferous sawnwood substitutes steel (40 percent), concrete (40 percent), and masonry and other materials (20 percent) in construction, and around 50 percent is used, for example, in packaging, joinery and carpentry and furniture, substituting various materials	89 million tonnes CO_2e/year	175 million m^3/year
Global production of wood-based fibres, substituting fossil-based fibres and cotton (Leskinen *et al.*, 2018)	The production of dissolving pulp grows at an annual rate of 3.9 percent to 2030, and 75 percent of it is used to produce man-made cellulosic fibres. The wood-based fibres consist of viscose (50 percent) and lyocell (50 percent) and replace polyolefins (75 percent) and cotton (25 percent) in clothing	11.3 million tonnes CO_2e/year	31 million m^3/year
Global construction of mid-rise urban buildings (Churkina *et al.*, 2020)	All new mid-rise urban buildings with 9.2–79.1 m^2 floor space per capita built between 2020 and 2050 are predominantly (90 percent) constructed using engineered wood products that substitute for steel and concrete	45–1 196 million tonnes CO_2/year	545—4 945 million m^3/year
The Russian Federation – low-rise wooden construction (Leskinen *et al.*, 2020)	The basis is a forecast of low-rise wooden building construction, evolving from 69 million m^2 per year by 2030 to between 128 and 183 million m^2 per year by 2050. Avoided emissions and roundwood equivalent are estimated on the basis of CLT use	20.3–23.7 million tonnes CO_2/year in 2030 37.7–62.8 million tonnes CO_2/year in 2050	53.1–61.8 million m^3/year in 2030 98.6–164 million m^3/year in 2050
Increased wood use in Japan (Matsumoto *et al.*, 2016)	Increase harvest of wood in Japan between 2010 and 2050 and enhanced use of wood for construction of buildings, furniture and for civil engineering	10.6 million tonnes CO_2/year	34 million m^3/year

As shown in Table 6.1, the amount of wood needed to substitute fossil-based or fossil-intensive products varies between studies and is strongly influenced by the assumed degree of product substitution. For example, Churkina *et al.* (2020) estimated that if all new mid-rise urban buildings in the world were predominantly constructed using engineered wood products, 0.5–5.0 billion cubic metres of roundwood would be needed per year. This represents vast amounts of wood, and actually exceeds the total current global level of wood production. Harvesting such large volumes of wood will significantly affect the carbon balances of forests and will very likely increase the competition for raw materials for different wood products. Such competition may lead to negative substitution effects, i.e. other wood products being substituted by (non-renewable) products. Overall, the climate change mitigation potential offered by product (or material) substitution depends on the product considered (e.g. the assumed floor space in construction), the size of the markets considered, and the degree of substitution that takes place. It should be noted that the avoided emissions in Table 6.1 exclude the effects on carbon storage in forest biomass, soil and wood products, but these emissions should be considered for a holistic understanding of whether increasing wood harvest to enable substitution will contribute to climate change.

6.3 Summary

Existing projections of the future production of wood products suggest a steady increase in the production of sawnwood, wood panels and paper and paperboard over the next decades for alternative global developments. However, existing projections for future forest product supply and demand dynamics suffer from uncertainties and knowledge gaps, concerning changes in consumer behaviour and the future market uptake of innovative wood products. A key question is if and how substitution by wood products will result in additional demand for roundwood, which will have implications for the carbon stored in forest ecosystems. Allocating large volumes of wood to specific applications will also likely increase competition for raw materials and may lead to negative substitution effects, i.e. wood products being substituted by other (non-renewable) products.

Take-home messages

- The future production of wood products suggests a steady increase in the production of sawnwood, wood panels and paper and paperboard over the next decades, although some structural change can be observed for certain products, linked to internet adoption.
- Projections for future forest products supply and demand dynamics suffer from uncertainties and knowledge gaps, concerning changes in consumer behaviour and the future market uptake of innovative wood products.
- There is still limited understanding on substitution effects at market, country and global level. Allocating large volumes of wood to specific applications will likely increase competition for raw materials and may lead even to negative substitution effects.

7 Knowledge and implementation gaps in forest product value chains

7.1 Forest product value chains

As introduced in Chapter 1, a circular bioeconomy in the context of forest products emphasizes the effective and efficient utilization of forest resources and their circularity. Unlike traditional economic models that assume linear systems (i.e. produce, use, discard) and infinite supply of resources, a circular bioeconomy model acknowledges an inherent question regarding sufficient availability of sustainably managed feedstock to meet growing bioeconomy demands for woody biomass. Growing global wood consumption will likely exert pressure on wood production systems and their sustainability, which could act as a driver for a more circular approach. This chapter identifies knowledge and implementation gaps in the global forest product value chain from a circular bioeconomy perspective.

A value chain describes the steps required to create a product from start to finish. When a product is observed in a circular bioeconomy setting, the value chain comprises the raw material base, the (eco-)design and manufacturing of products, their use and disposal, such as burning for bioenergy (Figure 7.1. Product value chain in a circular bioeconomy context). It also includes reuse, which is using a product anew without any intermediary processing or transformation, and recycling and recovery, which takes the product through some kind of processing or even transforms it into another type of product (Kalverkamp, Pehlken and Wuest, 2017). These together form the cascading use of products (Mair and Stern, 2017). Wood product value chains can be complex, with multiple transformations along the chain (e.g. from roundwood to sawnwood to engineered structural timber) and several processing residues and raw material side streams utilized as – or for generating – by-products (e.g. woodchips from sawnwood milling used to produce particle boards).

A value chain can be interpreted in general terms and globally for all forest products i.e. "a global forest product value chain". Such a value chain may have knowledge and implementation gaps when observed from a circular bioeconomy perspective (Figure 7.1. Product value chain in a circular bioeconomy context).

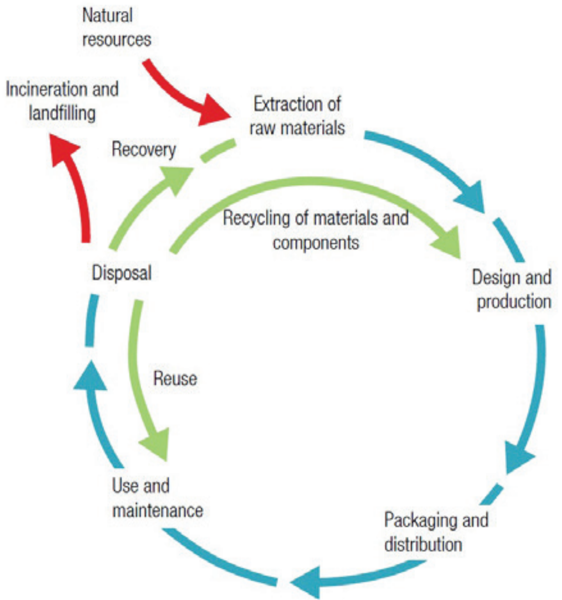

Figure 7.1. Product value chain in a circular bioeconomy context

Source: UNEP (2012)

In countries with advanced forestry industries, forest product value chains may already be well developed, with high degrees of resource utilization and efficiency. For example, in Finland, all parts of harvested trees are used for dedicated purposes (Finnish Ministry of Agriculture and Forestry, 2019), and various side streams and residues of industrial processes are exploited. This includes utilizing the forest industry's black and waste liquor in the preparation of chemicals and biofuels, using the ash from burning fuelwood as fertilizer, or using tree bark in glue manufacturing (Finnish Ministry of Agriculture and Forestry, 2019). Furthermore, towards the end of the value chain, wood product recycling systems can be well advanced, as in the case of newsprint recycling in some countries (Haggith *et al.*, 2018).

7.2 Production stage

The design of a product is important for determining the possible use, reuse and recycling of a product during its life cycle. Eco-design is about developing a product that will have a reduced environmental impact throughout its life cycle (Salo, Suikkanen and Nissinen, 2020), which includes extending its life cycle through cascading use. It is therefore connected to every stage in the value chain. Below, we give some examples to show how environmental impacts could be reduced through better product design:

- Wood poles, which are used worldwide for power and communications lines and street lighting, are traditionally made with roundwood. However, moulded wood poles would outperform other wood poles in terms of resource efficiency, as their production process does not result in residues and several parts of the tree could be used to make them (May, Günther and Haller, 2019).

- In construction, various composite wooden products are glued together using petroleum-based adhesives, which limit the possibilities for recycling the composite product. The use of other adhesives could expand the life cycle opportunities for reuse and recycling of forest biomass (Sathre and González-García, 2014).
- In wooden furniture, the selection of materials, their treatments and respective manufacturing processes all have considerable influence on the environmental impact over a product life cycle (Bovea and Vidal, 2004; Çinar, 2005), which could be taken into account comprehensively in the product design.

These examples show that it is possible to improve the eco-design of wood products. One important challenge for eco-design is providing for cascading use in open market conditions, because the producer of the initial product may not reap any benefits from the "new" product made by another manufacturer (Vis, Mantau and Allen, 2016). Also, a producer may simply lack knowledge of any eventual cascading use of the product, which complicates eco-design (Jarre *et al.*, 2020).

7.3 Cascading

Additional knowledge and implementation gaps can be identified in the later stages of the global forest product value chain. Cascading use is "a strategy to use raw materials such as wood or other biomass in chronologically sequential steps as long, often and efficiently as possible for materials, and only to recover energy from them at the end of the product life cycle" (Dammer *et al.*, 2016). It consists of reuse, recycling and recovery. It is understood that higher degrees of cascading use could lead to increased resource efficiency, alleviating pressures related to feedstock availability. For example, paper is commonly recycled up to seven times before the wood fibre properties deteriorate too much for further use, which reduces the need for virgin fibre. However, for other types of wood products, cascading use seems to be less developed, and biomass may be recovered for energy straight after the first product application (Dammer *et al.*, 2016), which forms an implementation gap. This kind of "single-stage cascade" can be the case when there is no effective sorting system for wood waste. In contrast, and in addition to the example of paper recycling above, a "multi-stage cascade" occurs when a product goes through at least two life cycles before being disposed of. For instance, structural timber used in construction could be afterwards used for particleboard production, and then finally burned. Yet it is also possible that biomass is used directly as bioenergy, which does not constitute cascading use. In fact, 49 percent of global roundwood removals are utilized as bioenergy in this way (FAOSTAT, 2020). This can be seen as an implementation gap in effective cascading use, as it inhibits the reuse and recycling of wood. Replacing some of this bioenergy use with other renewable energy sources could free up immense quantities of wood for material uses, which could also eventually be cascaded. Limited or no cascading can be due to a lack of incentives for cascading, or the existence of incentives that steer biomass to renewable energy production, plus deficiencies in – and difficulties in establishing – effective waste wood collection and sorting systems (Jarre *et al.*, 2020; Vis, Mantau and Allen, 2016).

The implications of cascading use (or lack thereof) are still not fully understood with respect to carbon storage in products, which is of relevance to the bioeconomy. Harvested wood products contain carbon, and the longer the products are retained in use, the longer the carbon is stored and not released to the atmosphere, which contributes to climate change mitigation. One study estimated that CO_2 emissions savings in Europe in the use of sawnwood, wood-based panels and paper and paperboard could be augmented by 17 percent if the average lifespan and recycling rate of these products were increased by approximately 20 percent (Brunet-Navarro, Jochheim and Muys, 2017). In addition, promotion of wood use to substitute for GHG-intensive materials, such as in buildings and furniture (Churkina *et al*., 2020; D'Amico, Pomponi and Hart, 2021; Geng *et al*., 2019), can help store carbon and mitigate climate change, contributing to a bioeconomy. However, public policies do not yet systematically pursue this aim to unlock the potential in the global forest product value chain (Vis, Mantau and Allen, 2016).

From circular bioeconomy and climate change mitigation perspectives, the lack of cascading can be problematic, as it is generally considered more desirable to recycle and retain a product in use for as long as possible before its final utilization in energy generation (Bogner *et al*., 2007). Technical challenges can also limit effective cascading. For example, when buildings are being disposed of through demolition, any structural timber therein becomes broken and mixed with other materials. Although usable for chipping for particleboard or fibreboard production, this means downcycling the valuable solid material (Hradil *et al*., 2014). The timber value could be better retained by deconstructing instead of demolishing. Generally, upcycling waste wood can provide an incentive for higher recycling rates (Irle *et al*., 2019). Also, wood can be treated with preservatives to prevent or slow down material decay (Sathre and González-García, 2014). Preservation can be achieved using different chemicals which can, however, be toxic. In turn, the wood will be considered contaminated, which limits its recycling options (Jarre *et al*., 2020). Even so, emerging methods could enable the effective detection and removal of preservatives in wood (Fraunhofer Institute, 2017). Furthermore, the use of CLT and the application of a modular building design can contribute to enhanced cascading use of wood materials (Hartley and Blagden, 2007; Melton, 2020; Sustainable Construction Services, undated). Such issues link back to eco-design, where a product's later life cycle stages can be taken into consideration, for example, through use of environmentally low-impact materials (Ramage *et al*., 2017; Sathre and González-García, 2014).

7.4 End-of-life

In the context of cascading use, the final "ideal" utilization of wood products, after they have been reused or recycled as many times as possible, is usually considered to be recovery for energy (Dammer *et al*., 2016; Jarre *et al*., 2020). Thereafter, it may be possible to use the ash from burning for fertilizer, which completes a "cradle-to-cradle" system (Thonemann and Schumann, 2018). Wood is also landfilled, although this option is considered to be the bottom of the waste management hierarchy (Kalverkamp, Pehlken and Wuest, 2017) (Hossain and Poon, 2018). When wood is landfilled, the material is no longer used and there is a risk of carbon dioxide and methane emissions due to the gradual decomposition of the wood. However, methane released by landfilled wood can be captured for energy generation (Morris, 2017). Better knowledge is still needed for the end-of-life options of different types of wood products and wastes.

The recycling rate of all paper and paperboard between 2015 and 2019 was 67 percent in both Europe and North America, 49 percent in Asia and Oceania, but only 28 percent in Africa and 19 percent in Central and South America (FAOSTAT, 2020). These figures could be taken as indicative of the overall infrastructural and systemic capacity for cascading use and management of waste wood. Documented examples of good practices from outside Europe and North America are scarcer and appear rather anecdotal. Examples include a construction waste management company in Japan transforming demolition wood waste into chips for fuel, boards and papers (Yolin, 2015), the production of particle boards made of waste wood and epoxy based ink waste in Brazil (Souza *et al.*, 2018), or the recycling of support posts during wooden bridge renovation in Myanmar (Fraunhofer Institute, 2017).

7.5 Summary

A circular bioeconomy in the context of forest products emphasizes the effective and efficient utilization of forest resources and the use, reuse, and recycling of forest products. Various examples of eco-design, cascading use, or management of waste wood exist particularly in European and North American contexts (European Commission, 2018c; Falk and McKeever, 2004), but there is still a need to strengthen the eco-design, recycling, cascading use and management of waste wood to reduce the environmental impact throughout the product's life cycle. From a circular bioeconomy and climate change mitigation perspective, the lack of recycling and cascading can be problematic, as it is generally considered more desirable to retain a product or its material in use for as long as possible before final utilization in energy generation.

Table 7.1. Knowledge and implementation gaps in different wood product value chain steps

Value chain step	Knowledge gaps	Implementation gaps
Production	Producers may lack knowledge of any potential reuse and recycling of a product, which complicates eco-design.	Adhesives are used in the production of wood-based products, which may cause pollution. Use of environmentally compatible (forest-based) adhesives could expand the life cycle opportunities for reuse and recycling of forest products.
Cascading	Incomplete understanding on the impact of cascading on climate change mitigation and other environmental impacts in many parts of the world.	Around half of global roundwood production is used as fuelwood, which inhibits its cascading use of wood. Ineffective or non-existent collection and recycling systems inhibits the reuse of forest products.
End-of-life	Lack of understanding of the comparative advantages and disadvantages of different end-of-life options for wood, such as incineration and landfilling.	Landfilling wood at the end of a product life prevents the use of forest product as a raw material. Recycling of forest products should be preferred over incineration, where possible.

Developing awareness of the various knowledge and implementation gaps in the global forest product value chain, while exploring and piloting different approaches to address them is crucial when it comes to ensuring the sustainability of a circular forest-based bioeconomy. Therefore, the issue requires attention from policy makers, the industry and the research community alike to establish ways forward that consider the needs of different stakeholders.

Take-home messages

- While in some countries forest product value chains can be advanced and highly efficient, several knowledge and implementation gaps can be observed in the global forest product value chain.
- Existing knowledge and implementation gaps concern eco-design and manufacturing, cascading use, and end-of-life.
- These gaps are commonly related to policy, technical or societal and systemic issues.
- Developing awareness of the gaps and the importance of addressing them among different stakeholders could be a first step towards enhanced circularity in the bioeconomy.

8 Conclusions and recommendations

8.1 Main conclusions

There is a growing understanding that a rethink of the global economic system is necessary to address the root causes of the unsustainable use of natural resources and achieve sustainable development. The bioeconomy has emerged as a concept for tackling challenges such as the overconsumption of an overreliance on non-renewable natural resources. Forests and the forest sector are important components of a bioeconomy. This study addressed the role of forest products in the global bioeconomy and their contribution to replacing fossil-based and GHG-intensive products. It explored how substitution by forest products could strengthen sustainable development.

The forest sector has been long manufacturing numerous products that are used in everyday life. For some of these products, significant changes have occurred recently. Graphic paper is one product group marked by structural change, where demand has stabilized or is even declining in some world regions, linked to the adoption of internet and electronic media. New products and technologies are emerging that aim to increase the added value of wood products, decrease the carbon and water footprint of products and processes, reduce pollution and waste generation, and improve circularity. Engineered wood products and wood-based textile fibres are two such emerging forest product categories. The production and consumption of engineered wood products are rising, mainly due to increased application in wood-frame multistorey construction, facilitated by the possibility of pre-fabricating elements and modules that can readily be used in construction. Lyocell fibres are modern wood-based textile fibres that have properties like viscose and polyester yet are more environmentally friendly in production. With an increasing demand for textile fibres, modern wood-based textile fibres offer a suitable alternative. Forests also provide many NWFPs with high economic value.

There is strong evidence at the product level that wood products are associated with lower GHG emissions over their entire life cycle compared to products made from GHG-intensive and non-renewable materials. Wood and wood-based products are generally associated with lower fossil and process-based emissions when compared to non-wood products. However, most studies in the literature focus on construction and significantly less information exists for other traditional forest products such as paper for printing, writing and packaging, or emerging forest products. Furthermore, most of the studies from which substitution factors could be derived focus on North America and the Nordic countries in Europe, and the substitution effects by wood products in many other areas of the world are not well understood, despite their relative importance in the global wood markets. Importantly, substitution effects depend on the type of wood product being considered, the type of non-wood product that it substitutes, production technologies and efficiencies and the end-of-life management of wood and non-wood products, and generalizations are not therefore straightforward. There is still limited understanding of the substitution effects at the level of markets, countries or global regions, presumably due to limited information on end uses of wood and the difficulty in determining which materials are substituted.

While forest products can provide benefits when compared to the use of non-renewable, GHG-intensive materials, there are also potential risks associated with the increased production and consumption of forest products. The production and extraction of raw materials needed to manufacture products has economic, social and environmental impacts. Sustainable, climate-smart forest management is needed to meet the needs of a growing population, while supporting biodiversity and other ecosystem services. For a holistic understanding of the benefits of substitution by wood products, it is crucial to also consider the effects on carbon storage in forest biomass, soil and wood products, as well as their permanence and potential leakage effects. Allocating large volumes of wood to specific applications will likely increase competition for raw materials and may lead even to negative substitution effects, meaning that wood products are substituted by other (non-renewable) products.

To strengthen the role that forest products can play in a circular bioeconomy, there is a need to improve the manufacturing (including eco-design), use, reuse, recycling of forest products, and management of waste wood to reduce the environmental impact over the product’s life cycle. Developing awareness and addressing knowledge and implementation gaps in the global forest product value chain is crucial in ensuring the sustainability of a circular forest-based bioeconomy.

8.2 Opportunities to enable and accelerate wood-based product substitution for high greenhouse gas-based products

Whenever there is change, there is the resistance thereto, as an inherent part of human nature. This resistance is shown in the way that vested interests can oppose change as it threatens old ways of doing things, and proven business models and investments, even when they are losing relevance in the transition to more sustainable systems. This inertia should be actively addressed and tackled. To strengthen the contribution of product substitution to sustainable development, there are numerous factors that may enable or boost the substitution of fossil-based or GHG-intensive products with forest products.

Enabling factors include efforts or initiatives to stimulate technological change (or innovation) that can lead to the development of innovative and climate-friendly bio-based products and technologies (Lovrić *et al.*, 2020). Other enabling factors include allowing (or restricting) certain economic activities to take place, or facilitating holistic product design approaches by updating the existing capacities of designers, architects, general education and consumer awareness. Substitution can be boosted through incentives to produce or consume less fossil and more bio-based alternatives, or through investments in innovation and public-private partnerships. Finally, consumer behaviour is a key factor that may boost the uptake of bio-based or forest products. While consumers may be aware of environmentally friendly alternatives, promotion and marketing will, as in any commercial environment, be needed to guide choices towards sustainable options.

Ultimately, the biggest constraint on the price-competitiveness of bio-based products comes from cheap oil. Away from niche markets where a higher price is acceptable due to other aspects such as appreciation of sustainability or trendiness, mass adoption of bio-based alternatives could be promoted and incentivized, for example through avoiding subsidies or punitive taxes for non-renewables, regulations, improved information, and marketing, and so on. The forest sector, or the bio-based sector more generally, should avoid constraining its substitution potential further through intra-sectoral competition, whereby it competes with other bio-based alternatives and thus loses out on the opportunity to outcompete alternatives whose replacement would achieve higher substitution benefits. Other constraints to be overcome concern the costs involved in modernizing tools and the workforce to adopt new materials and techniques, and bias from consumers who sometimes see bio-based products as less durable or less desirable due to (cultural or historical) negative connotations.

The following sections describe issues that should be addressed to strengthen the contribution of substitution to sustainable development.

Technological innovation

- **Research** is the basis of industrial and product innovation. Investments in research can speed up the development of innovative and climate- and environmentally friendly bio-based products and technologies.
- Support mechanisms can facilitate **shorter technological innovation cycles** and the time to bring new products and processes to the market.
- **Cooperation between scientific, industrial and financing actors** can foster the uptake of innovations.

Consumer behaviour

- **Consumer awareness** is important, as informed consumers will make conscious choices on climate-friendly and sustainable options. Efforts such as education, marketing and so on can help to increase consumer awareness by highlighting the benefits that forest products could provide over non-renewable, fossil-based and GHG-intensive products. Promotion and marketing could also highlight the importance of other environmental impacts, such as the difference in pressure on water use, eutrophication, pollution, and so on.
- **Consumer attitude.** In many markets, consumers have become more climate and environmentally aware. However, discrepancies between awareness and actual purchases/practices can be observed. It is important to translate awareness into behaviour, for example by improving access to and availability of environmentally responsible products.
- **Lack of knowledge** regarding the importance of reducing consumption of fossil and mineral-based or GHG-intensive products needs to be overcome among the admass. It is important to inform consumers how their behaviour can affect product substitution and contribute to sustainable development.

Market development

- **Vested interests**. When old business models are in place, existing industries, infrastructures and the related lobbies may not be keen on investing in innovation for a transition to a new, more sustainable (economic) system. More and more companies are becoming aware, however, that business models based on unsustainable practices cannot be perpetuated and that practices need to change.
- **Private sector alliances**. Supply steered by large retailers can catalyze change in certain industrial sectors. Examples of such alliances are the World Business Council for Sustainable Development (WBCSD) or the TreeToTextile AB joint venture.
- **Intra-sectoral collaboration**. Substitution most clearly happens when the wood product substitutes the non-wood product at the market level but when, through market forces, wood products with lower substitution potential end up substituting wood products with a higher substitution potential, there may not be any substitution impact in practice.
- **Corporate and social responsibility** can encourage sectors to produce and use more sustainable alternatives to replace materials and products that perform less well according to environmental and socioeconomic indicators.
- **Capacity building** needs to target professionals to update their knowledge of climate-smart and sustainable options. Support for the specialized (re)education of the labour force – to work with wood construction, for example – would result in a faster pace of change.

Society

- **Civil movements** can boost support and demand for environmental or climate-friendly options, such as Wangari Muta Maathai in Africa, Chico Mendes in South America, Sunderlal Bahuguna in India, or Greta Thunberg in Europe. They all inspired many people to become more environmentally aware, and to address climate goals and sustainable development.
- **Crisis and natural disasters** can trigger the realization that the transition from fossil fuels needs to speed up. One example is the high importance politicians from the European Union gave to the Green Deal, due to an acceleration of catastrophic climate events and trends, and to build back better after the global COVID-19 pandemic.
- **High-level initiatives** can help increase awareness of the bioeconomy and substitution potential and can enable developing nations onto a path towards self-reliance and product diversification to supply both domestic and export markets with climate-positive products.

Finance and insurance

- **Insurance.** Insurance companies need to be part of the solution and should be encouraged or supported to reassess risks related to product substitution. The unwillingness to insure high-rise wooden constructions can form a serious barrier and to counter this, insurers need to be properly informed of wooden construction risks and benefits (Glockling, 2020).

- **Investment and public-private partnerships**. For many products, such as biochemicals, the most crucial boost would come from investment in production technologies and piloting. However, this is often lacking. Early detection of promising new technology developments and their promotion among private and/or public investors might help to overcome this.
- Investors most often require **transparency from stock-listed companies on the climate impact of their products.** Ultimately, a requirement for stock-listed companies to declare their impacts on the goal of reaching net zero emission targets by 2050 will quicken divestment from fossil-based in favour of bio-based alternatives.

Governance, legislation and regulation

- There needs to be a **political will for change** to regulate in a new direction. A range of policy instruments exist to support the development of a bio-based economy. An example is given in Figure 8.1, with specific examples for the wood construction sector.

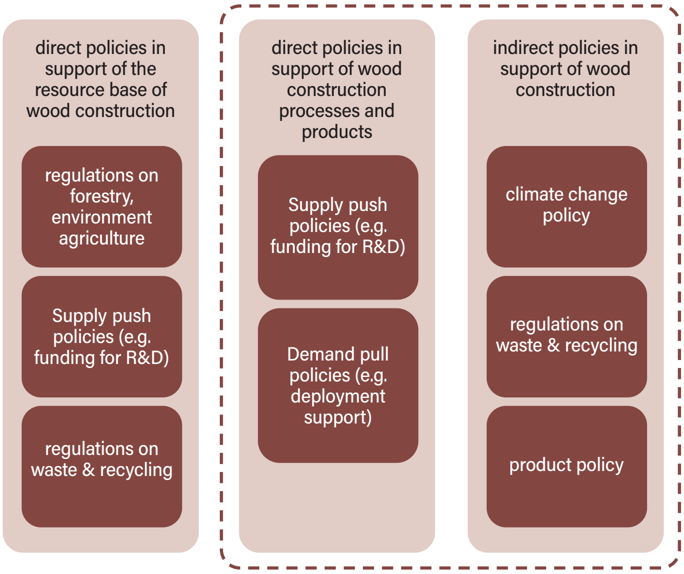

Figure 8.1. Range of policies existing to support wood construction
Source: Vihemäki *et al.* (2019)

- **Subsidies and tax incentives**, both positive and punitive, can be used respectively to encourage production of sustainable bio-based products or, on the contrary, to discourage the use of fossil-based products, the price of which is still set by the ease of access to the raw material, thereby undermining the competitiveness of renewable products.
- A legal requirement (e.g. in a building code or targeted at specific consumer goods) to **include sustainability considerations in the product design stage** would incentivize product developers, designers and architects to take the environmental impacts of the product into account.

- A legal requirement for **product labelling for environmental impacts**, thereby enabling consumers to make environmentally and climate-sound choices. For example, the energy efficiency ratings required for buildings in the European Union help people make a choice when purchasing real estate and also influence action to improve the buildings' energy efficiency. The best impacts would be achieved when product labels are the result of international cooperation towards standardization.
- **Targets** specifying a minimum amount of bio-based resource to be included in a raw material mix can introduce new products and technology development. Gradually, such targets can be increased, allowing industry to scale up.
- **Public procurement rules** (e.g. requiring the use of sustainably produced wood in the construction of public buildings) would incentivize designers, architects and construction companies to substitute non-renewable, emission-intensive products by wood products from sustainably managed forests.
- **High-level intergovernmental initiatives** (e.g. United Nations Sustainable Development Goals) and **conventions** (e.g. on climate, biodiversity and the fight against desertification) can contribute to developing a circular bioeconomy, especially if combined with commitments from governments and national policy targets that are reported and monitored at national and international level.

8.3 Recommendations to strengthen the contribution of product substitution to sustainable development

To strengthen the contribution of product substitution in a circular bioeconomy, recommendations are provided for specific actions that could be taken by the private sector, governments of countries and regional economic integration organizations, and through international cooperation bodies.

Recommendations targeting the private sector:

- Avoid non-sustainable, short-term profit maximization and instead **focus on long-term responsible and sustainable production that contribute to achieving the SDGs.**
- **Contribute to improved understanding of how the environmental impacts of forest products compare with products made from other materials**. This includes information on production technologies and efficiencies from traditional forest products such as paper and packaging, as well as innovative forest products (especially chemicals, textile fibres, plastics and composites). Substitution effects need to be better understood at both product and market level.
- **Provide transparent and accurate information on the climate and other environmental impacts of products over their entire life cycle,** applying scientific methods and standards to strengthen understanding of how responsible production can contribute to SDGs.
- **Include sustainability considerations in the product design**, aiming to take the environmental impacts of the products into account over their entire life cycle, from extract-

ing the raw material down to possible reuse and recycling of the product. This includes designing forest products that can remain in use as long as possible.

- **Invest in developing efficient production processes and technologies that optimize material use, avoid pollution and reduce the environmental footprint of products.** This should include wood sourcing through sustainable forest management practices that carefully consider biodiversity, long-term carbon stock and sinks in forest ecosystems and wood products, forest productivity, and inclusive socioeconomic development, as well as the manufacturing of products.
- Substitution provides benefits for climate change mitigation when wood products substitute fossil-based or GHG-intensive products at the market level. To foster the substitution of fossil-based or GHG-intensive products by wood products (or other bio-based products), **intra-sectoral competition should be avoided** so that forest products do not compete for market share with other environmentally beneficial products; **intra-sectoral collaboration should be stimulated**.

Recommendations targeting governments of countries and regional economic integration organizations:

- **Incentivize and encourage responsible production and consumption of sustainable bio-based products** and discourage the use of non-renewable, fossil-based and GHG-intensive products (e.g. through taxes on emission-intensive products, abolishing subsidies for fossil energy).
- **Consider the important role that forests and forest products play in a functioning, circular bioeconomy.** This role includes carbon storage by forest ecosystems, as well as carbon storage by wood products and product substitution. It is important to find the right balance between short and long-term goals, and between the need for wood production, biodiversity protection and the provision of other important ecosystem services. **Exclude actions that favour climate change mitigation locally, but that lead to deforestation or forest degradation elsewhere because of international trade.**
- **Design and implement procurement procedures that prioritize sustainable products and services** over other alternatives, for example by including a sustainability scoring system in bidding or purchase evaluation processes.
- Facilitate development of efficient wood cascading, durable use and recycling systems, and avoid landfilling.
- Foster research activities to **improve the understanding of substitution effects at product and market level for all product categories**, including emerging products, as regards climate and other environmental impacts, and the effects on achieving the Sustainable Development Goals.
- **Strengthen cooperation between scientific, industrial and financing actors** across national boundaries to achieve **shorter technological innovation cycles, diversified value chains** and to **facilitate cooperation across traditional sectoral boundaries**.
- **Upgrade educational curricula** at all levels to encourage sustainability thinking from an early age and to ensure that engineers, architects, designers and other professionals and practitioners will learn the skills to enable (transformation to) a sustainable future.

- **Promote capacity building for professionals**. Governments should support and encourage specialized training, retraining and retooling of professionals, to update their knowledge of climate-smart and sustainable options and to enable them to take part in new economic activities enhancing the forest-based bioeconomy.
- **Improve consumer awareness** by providing accurate and clear information (e.g. through product labelling) on the possibilities and advantages of sustainable consumption patterns.

Recommendations targeting international cooperation bodies:

- **Facilitate comparative studies and global data collection efforts for monitoring the bioeconomy** to assess achievements and address knowledge and implementation gaps to foster the transformation to a sustainable, circular bioeconomy.
- **Facilitate knowledge exchange** to strengthen the capacity of countries and private sectors in the transformation to a sustainable, circular bioeconomy by sharing technical knowledge, good practices and innovations to mitigate climate change, reduce or prevent pollution and address other trade-offs for a bioeconomy benefiting the environment.
- **Promote international partnerships** between academia, industry, finance and public administration to seek how the transformation to a sustainable, circular bioeconomy could be achieved through sustainable and responsible production and consumption patterns, particularly in sectors where large substitution potentials exist.

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10 Appendix 1- The bioeconomy and the role of forest products around the world

This Appendix provides an overview of understanding of the bioeconomy and the role of forest products around the world, specifically in Australia, Brazil, China, Ethiopia, the European Union, Ghana, New Zealand, the Russian Federation, Turkey, and the United States of America.

10.1 Australia

Bioeconomy-related efforts

As of 2020, Australia does not have a national bioeconomy strategy; nor is there one under development. Nonetheless, the Australian Government has developed measures that foster the bioeconomy as an enabler across a number of sectors, such as agriculture, bio-based chemicals and packaging, biofuels and bioenergy, biorefining, forestry, and the pharmaceutical industry (FAO, 2018).

Perhaps the most relevant strategy to the forest-based bioeconomy is the "Opportunities for Primary Industries in the Bioenergy Sector – National Research, Development and Extension Strategy", launched at the national level in 2011, which is mainly concerned with fostering sustainable supply chains of biomass feedstocks for bioenergy conversion (Rural Industries Research and Development Corporation, 2011). From a forestry point of view, the strategy identifies residues from forestry operations as an existing feedstock for bioenergy conversion and dedicated short-rotation forestry as an emerging feedstock. In 2014, the strategy was elaborated into an implementation plan, which also recognizes the forest industry approach to sustainability, including sustainability certification schemes, as providing a valuable precedent for bioenergy sustainability (Rural Industries Research and Development Corporation, 2014). In addition, the Forest Industry Advisory Council established by the Australian Government has recognized a key role for the forestry sector in the transition to a bioeconomy in Australia (Commonwealth of Australia, 2016).

At a sub-national level, the Federal State of Queensland adopted a bioeconomy-related strategy in 2016 with potential implications for forests and forestry. The "Queensland Biofutures 10-Year Roadmap and Action Plan" connects the term biofutures to industrial biotechnology and the bioproducts sector, and focuses on sustainable economic growth therein (State of Queensland Department of State Development; Manufacturing; Infrastructure and Planning, 2016). The policy paper notes native and plantation forestry and sawmill residues as feedstocks for generating sustainable bioproducts such as textiles, chemicals, fuels and bioplastics. It also highlights the "access to millions of hectares of suitable growing land to support the cultivation and management of crops and plantation forestry" in Queensland as well as all-year-round growing conditions (State of Queensland Department of State Development; Manufacturing; Infrastructure and Planning, 2016).

In sum, forest-based bioeconomy-related measures in Australia are dispersed in national and regional initiatives. None of them specifically refer to the "bioeconomy" nor are they forest-focused, but they nevertheless show potential for a forest-based bioeconomy. At the national level, their focus has been bioenergy. Several industry associations have also developed bioenergy-related initiatives, although these have not been adopted by public authorities (Bioökonomierat, 2015).

Focus of the bioeconomy in Australia

The bioeconomy-related measures launched in Australia are research and development-oriented and they primarily address biotechnology, innovation and bioindustry. The "Queensland Biofutures 10-Year Roadmap and Action Plan" specifically refers to industrial biotechnology. As such, the various measures focus on bioenergy, innovating bioprocesses and bioproducts, as well as fostering sustainable economic growth and job creation, particularly in rural areas.

10.2 Brazil

Bioeconomy-related efforts

Until recently, Brazil had a number of policies fostering the bioeconomy, but no integrated strategies focused on the subject. In 2016, the "National Strategy for Science, Technology and Innovation" was created. The National Strategy, in force until 2022, is a medium-term guide that aims to assist in the preparation, implementation and monitoring of actions in science, technology and innovation in bioeconomy (MCTIC, 2016).

In 2018, the "Action Plan for Technology and Innovation on Bioeconomy" was established to implement the "National Strategy for Science, Technology and Innovation" and to ensure the promotion of a national bioeconomy by creating governmental bodies specifically for this area (MCTIC, 2018). The Action Plan aims to promote social, economic and environmental benefits, filling essential knowledge gaps, fostering innovation and providing conditions for the strategic insertion of the Brazilian bioeconomy within the global scenario (MCTIC, 2018). The Action Plan is divided into three main action fronts. The first is focused on scientific and technological development for the sustainable production of biomass, including the use of residues, as well as the genetic improvement of native species for bioproducts. The second action front aims to promote innovation in bioindustries through the scientific and technological development for biomass processing. Finally, the third action front promotes the development and manufacture of high added value bioproducts, especially chemicals from biomass, and aims to consolidate the circular bioeconomy.

The Action Plan is part of a larger framework in which several national initiatives aim to meet the goals set out in the 2030 Agenda for Sustainable Development by the United Nations. In addition, it takes into consideration the commitment made by the Brazilian government to the Paris Agreement (MCTIC, 2018), where the country made a pledge to reduce GHG emissions by 43 percent by 2030 (Federative Republic of Brazil, undated). The Action Plan takes into account these commitments while promoting the economic activities stemming from innovation and the development of more sustainable products, processes and services based on biotechnology.

Regarding the forest bioeconomy, Brazil does not currently have any policies or action plans designed specifically for this sector. However, the existing Action Plan for Technology and Innovation on Bioeconomy promotes several types of biomass-based activities and is not restrictive when it comes to the source of biomass, whether it is from agriculture, forestry or fisheries (MCTIC, 2018). In addition, the National Strategy focuses on using biomass as feedstock to substitute fossil-based raw materials in the production of food, feed, chemicals, fuel, energy and other materials, some of which could be applied to the forest sector.

Focus of the bioeconomy in Brazil

The bioeconomy in Brazil is associated with the development of biotechnology. According to the National Strategy (MCTIC, 2016), the bioeconomy in Brazil has as five main targets:

- increase the productivity of biological systems based on innovation;
- increase the competitiveness of the national bioeconomy in a global context;
- reduce regional asymmetries in production and access to science, technology and innovation;
- develop innovative solutions for productive and social inclusion; and
- strengthen the foundations for promoting sustainable development.

To achieve this, the National Strategy proposes to (i) stimulate basic scientific and technological research; (ii) modernize and increase the infrastructure for the development of science, technology, and innovation; (iii) increase financing for science, technology and innovation; (iv) prepare, attract and retain skilled workers; and (v) promote technological innovation in companies. The country's wood industry is constantly investing in innovation and lately the focus has been on bio-based products that represent more sustainable alternatives to traditional products. The investments in innovation aim to add value to forest resources and to better use industrial side streams by developing the nanocellulose and lignin value chains, and by producing high value-added bio-based products such as fuel, oils, nanofibres and textiles. In 2019, 54 percent of companies offered their employees training related to the improvement of manufacturing processes and products (IBA, 2020). These advancements are important considering that the wood industry sources more than 90 percent of their raw material from the 9 million hectares of planted forests and that the sector is committed to recovering degraded areas and preserving the almost 6 million hectares of protected forest areas (IBA, 2020).

Besides the area of the bioeconomy associated with biotechnology development – and the focus of the National Strategy – part of the bioeconomy in Brazil is dedicated to the production of NWFPs. This area of the bioeconomy is very much regionalized, and an important part of the economic activities in forest-dependent communities. In 2017, it generated around USD 240 million. Among the NWFPs from native species, açai berry, yerba mate and Brazil nuts are the three most important products in terms of monetary value (Brazilian Forest Service, 2019).

10.3 China

Bioeconomy-related efforts

In China, discussion on the bioeconomy strives to find a balance between economic development and environmental protection. The aim of shifting from a fossil-based economy to a more environmentally sustainable economy was included in the Chinese National Strategy in 2007. Since then, the green economy, circular economy, and low-carbon economy have all been discussed as possible pathways to achieving a sustainable development model.

Bioeconomy is a new concept in China with focus on the biotechnology industry (Kallio *et al.*, 2020). The concept of forest bioeconomy has rarely been used and has often only been referred to as forest bioenergy. There are no direct, comprehensive strategies or action plans related to forest-based bioeconomy, but many on the circular economy and low-carbon economy.

Forestry is recognized as an important sector that can contribute to achieving national SDGs and climate change goals by 2030. Most of the efforts are focused on afforestation to increase the carbon sink, providing sustainable raw materials and developing forest bioenergy. Forest coverage and stock were included in the various national planning and strategy documents (summarized in Table A1). Despite the forest industry being still largely dominated by a labour- and capital-intensive model, some changes regarding the potential substitution of fossil-based raw materials can already be observed. The industry is starting to use more paper-based products due to new regulations to reduce plastics consumption, to organize the collection and recycling of used plastics, and to find bio-based alternatives to fossil-based plastics.

Table A1. China's bioeconomy-related key strategic objectives by 2020, 2030 and 2050

Time frame	National strategy	Key objectives		
		CO_2 emission per capita	Non-fossil fuel energy proportion	Forest coverage and stock
Short term (2020)	Short term (13th Five-Year Plan 2016–2020)	By 2020, decrease CO_2 emissions per capita to 40–45 percent below 2005 level (2009)	By 2020, increase non-fossil fuel energy to around 15 percent, reduce proportion of coal in energy structure to below 65 percent	By 2020, increase forest coverage rate to 23 percent with forest stock reaching 16.5 billion m^3, and 9.5 m^3/ha
Medium term (2030)	National target of SDGs	By 2030, reach CO_2 emissions peak level, decrease CO_2 emissions per capita to 60–65 percent below 2005 level	By 2030, increase non-fossil fuel energy to around 20 percent, reduce proportion of coal in energy structure to below 50 percent	By 2035, increase forest coverage to 26 percent, with forest stock reaching 21 billion m^3, and 105 m^3/ha
Long term (2050)	19th National People Congress report by President Xi Jinping	By 2050, annual CO_2 emissions largely decreased compared to peak level	By 2050, increase non-fossil fuel energy to around 50 percent, reduce proportion of coal in energy structure to below 30 percent	By 2050, increase forest coverage to a world average level of 30.6 percent, with forest stock reaching 26.5 billion m^3, and 120 m^3/ha

Focus of the bioeconomy in China

The bioeconomy in China is largely focused on the biotechnology industry. In 2007, China's Ministry of Science and Technology issued development strategies to speed up the development of the biotechnology industry. This industry was included among the industrial development priorities in the 12th (2011–2015) and 13th (2016–2020) National Five-Year Plans. The Biotechnology Innovation Plan, within the 13th Five-Year Plan, defines biomedical, biochemical, bioresources, bioenergy (including wood pellets), bio-agriculture, environmental protection, and biosecurity among the bioeconomy development priorities by 2020 (Ministry of Science and Technology, 2017). Highlighted by the 13th Five-Year Bio-industry Development Plan, the economic output of bioindustry will likely reach around USD 12 trillion by 2020, and account for over 4 percent of GDP, becoming a pillar industry in the national economy and largely contributing to employment growth (NDRC, 2017).

10.4 Ethiopia

Bioeconomy-related efforts

As for most African countries, the bioeconomy is still emerging as a concept in Ethiopia. At the moment, the country does not have a strategy or action plan solely designed for the forest-based bioeconomy. However, development of the bioeconomy is being considered within the larger context of a green economy and, in recent years, many bioeconomy-related strategies, policies and initiatives have been adopted by the government (UNDP, 2015). These include a Climate-Resilient Green Economy strategy (CRGE) (2011–2025), and a Growth and Transformation Plan establishing a new Ministry of Environment, Forests and Climate Change, and establishing the Ethiopian Biotechnology Institute.

The CRGE strategy seeks to build by 2025 a middle-income country status that is both resilient to the impacts of climate change and low in GHG emissions (Federal Democratic Republic of Ethiopia, 2012). The strategy identifies four strategic pillars for CRGE implementation, forestry being one of these pillars. The CRGE Initiative promotes, among other things, rural development, health, creation of employment in high-value-added production, local production of efficient stoves, and rural employment in activities such as afforestation/reforestation and forest management. The CRGE strategy sets the target for afforestation (2 million hectares), reforestation (1 million hectares) and the management of 4 million hectares of forests and woodlands (Federal Democratic Republic of Ethiopia, 2012).

The Growth and Transformation Plan also considers forestry as a key sector that can contribute to Ethiopia's industrialization goals, especially through expansion and the sustainable management of the forest resource base to feed the growing wood-based industries such as furniture and pulp and paper (National Planning Commission, 2016). This is because forest establishment and sustainable management not only contribute to economic goals, but also have significant potential to generate social and environmental benefits and reduce poverty in rural areas, while addressing land degradation, soil erosion and improving water filtration and retention. The forest-related targets in the Growth and Transformation Plan II include an increase of the country's forest cover to 20 percent and an increase in the contribution of the forest sector to GDP to 8 percent by 2020 (MEFCC, 2018).

In 2016, Ethiopia established the Ethiopian Biotechnology Institute under the auspices of the Ministry of Science and Technology. The Biotechnology Institute aims to steer appropriate and effective implementation of national biotechnology research and development, including a progressive vision, to deliver economic and welfare benefits through increased local production and supply of useful biotechnologies in line with national priorities across various sectors. Other strategies related to forest-based bioeconomy include the Bamboo Development Strategy and Action Plan (2019–2030) (EFCCC, 2019) and the National Forest Sector Development Program (MEFCC, 2018).

Focus of the bioeconomy in Ethiopia

The focus of the bioeconomy development in Ethiopia is on afforestation/reforestation, forest management, import substitution, biotechnology development, job creation and food security, as outlined in the CRGE and Growth and Transformation Plan targets. To achieve these targets, the government of Ethiopia, the private sector and international organizations have implemented several initiatives and activities to produce and utilize products and services from forest resources. For instance, in 2019, a privately owned company established a biorefinery plant with installed capacity of 12,000 litres per day of biodiesel from the jatropha tree. By 2025, the company plans to have ten biorefinery plants and its production capacity could reach 730 million litres per year. The Ethiopian Petroleum and Natural Gas Development Enterprise is also in the process of establishing similar refineries. Processing technologies are improving, and small-scale industries are being established across the country to produce different products from the moringa tree (e.g. food and soap), eucalypt (e.g. essential oils for the pharmaceutical industry) and bamboo (e.g. toothbrushes, matboards and bamboo shoots for food). Since 2011, the country has committed to restoring 22 million hectares of degraded land by 2030 (commitment of 15 million hectares to the Bonn Challenge, and 7 million hectares to the New York Declaration). This target includes the 7 million hectares of afforestation, reforestation and sustainable forest management set in the CRGE, as indicated in the previous section (MEFCC, 2018).

10.5 European Union

Bioeconomy-related efforts

The bioeconomy concept has received a lot of attention within the European Union. The European Union published its Bioeconomy Strategy in 2012 and an updated Bioeconomy Strategy in 2018 (European Commission, 2018b). The updated European Union Bioeconomy Strategy aims to develop a sustainable bioeconomy for Europe, strengthening the connection between economy, society and the environment, thereby addressing global challenges such as meeting the SDGs set by the United Nations and the climate objectives of the Paris Agreement. The European Commission defines the bioeconomy as "all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services". The European Union's Bioeconomy Strategy and its update have the following objectives:

- ensuring food and nutrition security
- managing natural resources sustainably
- reducing dependence on non-renewable, unsustainable resources
- mitigating and adapting to climate change
- strengthening European competitiveness and creating jobs

Compared to its first Bioeconomy Strategy, the updated Bioeconomy Strategy shifts understanding from substitution towards circularity and sustainability, and addresses the competing use of biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), encompassing multiple sectors and policies with a view to achieving policy coherence and synergies. The goal is a more innovative and low-emissions economy, reconciling demands for sustainable agriculture and fisheries, food security, and the sustainable use of renewable biological resources for industrial purposes, while ensuring biodiversity and environmental protection (European Commission, 2018b).

Forests represent one of the very few resources where Europe can boost its self-sufficiency. However, to advance the sustainable production and use of forest resources, there is a need for a strong knowledge base, innovative solutions, investment frameworks and favourable policy (Bell *et al.*, 2018). Related to this, the European Commission aims to ensure a coherent approach to the bioeconomy through different programmes and instruments including (among others) the Common Agricultural Policy, Horizon 2020, the Bio-Based Industries Joint Undertaking, European environmental initiatives, and the European Innovation Partnership on Sustainable Agriculture (European Commission, 2018b).

It should be noted that the European Union's Bioeconomy Strategy is implemented through sectoral policies at national and European level. For sectors like agriculture, energy and environment, the legal competence is transferred from the national level to the European Union, while forest policy remains a national competence. Nevertheless, the forest sector and forest-based industries are affected by a large number of sectoral policies and policy instruments, which affect distinct stages of the forest-based value chain (Aggestam and Pülzl, 2018).

In addition to the Bioeconomy Strategy, the European Union published its Green Deal in 2019. This aims to make the European Union economy sustainable by turning climate and environmental challenges into opportunities. While the Green Deal does not explicitly refer to bioeconomy or wood, it does refer to forest actions to fight climate change, mainly through forest protection and restoration.

Focus of the bioeconomy in the European Union

The bioeconomy in the European Union means using renewable biological resources from land and sea, like crops, forests, fish, animals and micro-organisms, to produce food, materials and energy. The forest-based bioeconomy encompasses traditional forest products, including forestry, wood products, pulp and paper, along with novel or new sectors, products and applications developed (e.g. the chemical industry, construction, pharmaceuticals and energy), and ecosystem services (e.g. hunting, recreation and water purification) (Lier *et al.*, 2019; Ronzon *et al.*, 2020) (Figure A1). Indicative of its importance in the European Union, the value added to the bio-based economy amounted to over USD 740 billion in 2017, all bioeconomy-related sectors considered, and it employed 17.5 million people (Ronzon *et al.*, 2020), of which 4.5 million work in the forestry and extended wood-based value chains (Robert *et al.*, 2020)..

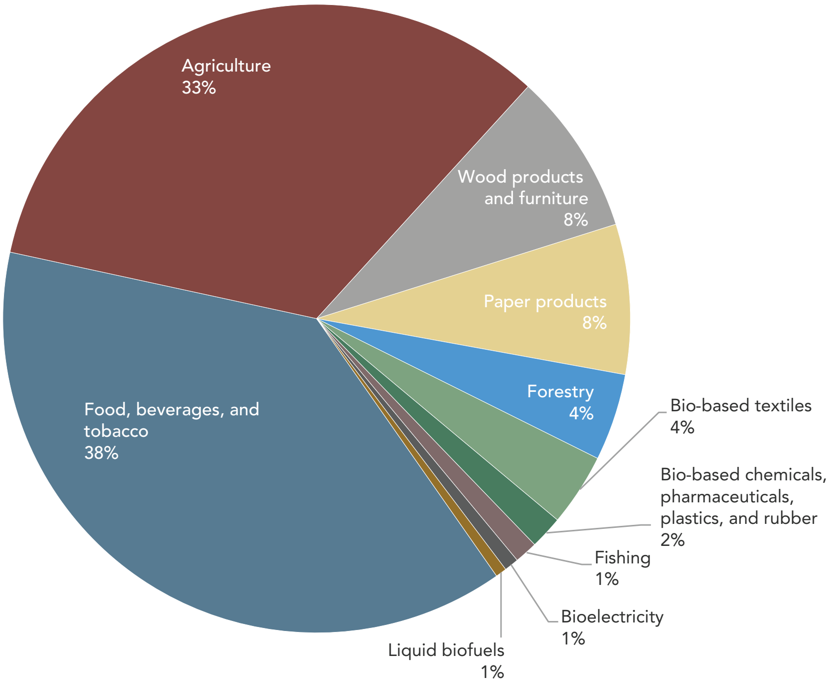

Figure A1. Value added to the bioeconomy in the European Union in 2017
Source: Adapted from Ronzon *et al.* (2020)

10.6 Ghana

Bioeconomy-related efforts

Similar to Ethiopia, Ghana does not have a forest-based bioeconomy strategy. The development of the bioeconomy is being considered within the larger context of a green economy and politically supported in the areas of bioenergy and biotechnology (UNEP, 2015). In 2010, the government published a bioenergy policy which aims to develop and promote the sustainable supply and utilization of bioenergy to ensure energy security for Ghana while maintaining adequate food security (Energy Commission, 2010). The policy has three thematic areas, namely: fuelwood, biofuel, and biomass waste to energy. Each thematic area is accompanied by the main issues, policy objectives and strategies to address the challenges and achieve the objectives. For instance, the main issues related to biofuels identified by the policy include the non-existence of a biofuel pricing mechanism, the absence of fiscal incentives for biofuel production, supply and marketing, and the high implementation costs of biofuel refineries. The suggested policy objective is to enhance the use of biofuels in the national energy supply mix. To achieve the objective, the policy outlines measures such as improving and sustaining local enterprises in the production and supply of biofuel feedstock, increasing biofuel supply in the national petroleum product mix, banning the importation of biofuels to encourage local production, establishing fiscal incentives for the promotion of biofuel production, supply and marketing, and establishing adequate storage and distribution facilities throughout the country.

The bioenergy policy is linked to the country's overarching development policy plans: the Ghana Shared Growth and Development Agenda (GSGDA) I (2010–2013) and II (2014–2017). GSGDA I and II have seven themes and one of the themes is Accelerated Agricultural Growth and Natural Resource Management. The strategic plan for GSGDA implementation has provisions for the transition to a green economy and *inter alia*, it stressed the following: expanding the Protected Area System, promoting regulatory or economic incentives, and improving institutional/policy reforms for the sustainable management of natural resources, including forest, water, land and coastal resources management.

Another important policy document is the Forestry Development Master Plan (2016–2036), which aims to promote the rehabilitation and restoration of degraded landscapes through plantations development and community forestry (Ministry of Lands and Natural Resources, 2016). Moreover, other policy documents also relate to the bioeconomy, such as the National Climate Change Policy, National Environmental Policy, Environmental Fiscal Reform Policy, National Climate Change Adaptation Strategy, and many others. For instance, Ghana's Renewable Energy Act aims to provide an enabling environment for the development, utilization, sustainability and adequate supply of renewable energy (from forest and agriculture-based resources) for the generation of heat and power in Ghana.

Focus of the bioeconomy in Ghana

The bioeconomy in Ghana is mainly focused on biotechnology, rural development, fossil fuel import substitution, development of bioenergy export capacity, and sustainable management of forest resources including afforestation and reforestation (PAGE, 2015). Though Ghana is endowed with abundant fossil fuel reserves, the country is a net importer of fossil fuels. To that end, Ghana has made clear that renewable energy has the potential to reduce the country's dependence on foreign energy sources, increase employment, and contribute to socioeconomic growth. In 2013, the Government of Ghana removed fossil fuel subsidies, freeing up public resources (about USD 1 billion per year) that will be used to promote, develop and utilize renewable energy sources, among other things (UNEP, 2015). Ghana also proposed tax on timber products to reduce deforestation, with the revenues to be ploughed into reforestation and afforestation activities. Since 2000, Ghana has established more than 20 jatropha tree plantations to produce biofuels and to contribute to rural development (Ahmed, Campion and Gasparatos, 2017).

10.7 New Zealand

Bioeconomy-related efforts

New Zealand published a national bioeconomy research strategy in 2017 called "Primary Sector Science Roadmap – Te Ao Tūroa". It aims at developing New Zealand's bioeconomy by growing and enhancing the country's industries involved in the primary sector, identifying science needs and themes in the process (New Zealand Ministry for Primary Industries, 2017). The strategy recognizes plantation forestry as an important carbon sink for climate change mitigation. It also directs science support to "new forest ecosystem services such as biorefinery forests, the use of short-rotation trees for biomass and bioenergy products" (New Zealand Ministry for Primary Industries, 2017). Apart from bioenergy, the strategy also encourages adding value and developing new product types, such as "high-performance specialty wood products from non-radiata pine trees" (New Zealand Ministry for Primary Industries, 2017). In terms of biotechnology, the strategy highlights geospatial software and technology and remote-controlled robotics in forestry, which contributes to worker safety and precision in harvesting technologies. Moreover, it notes the role of genetic improvement for enhancing productivity in forestry as well as making the industry more resilient against climate change, diseases and pests. The strategy additionally mentions new technologies in bioengineering and wood processing as an opportunity for meeting the demand for greater product value and diversification, particularly in biomaterials.

Aside from the national bioeconomy research strategy, Scion – a government-owned research institute – conducts research on the forest-based bioeconomy in New Zealand. Two of the institute's current research priorities are to (i) expand opportunities in the wood fibre, pulp, biopolymer, packaging and biochemical industries and from their biomass side stream, and (ii) increase New Zealand's energy security through the use of forest and waste biomass for bioenergy (Scion, undated).

Focus of the bioeconomy in New Zealand

The research strategy is focused on innovations, for example in advanced technology and genetics, in the country's primary sector, including forestry. Through this, the country aims at adding value to the primary sector and creating new products, thus fostering sustainable growth and natural resource management and enhancing the sector's international competitiveness.

10.8 Russian Federation

Bioeconomy-related efforts

Since 2010, the Russian Federation has been promoting the development of biotechnology and some aspects of the bioeconomy (Osmakova, Kirpichnikov and Popov, 2018). There is, however, no dedicated bioeconomy strategy. A State programme for the development of biotechnology (BIO2020) was created to modernize the country's economic sectors, as the Russian Federation was falling behind in development and implementation in these sectors (Government of the Russian Federation, 2016). The BIO2020 programme set up targets to be met by 2020 to help foster the development of biotechnology in several areas. Technology platforms gathered public, private, scientific and civil society institutions to collaborate on innovation. Of the first 25 approved Russian technology platforms, several relate to the forest-based bioeconomy, for example the Bioenergy Platform and the Russian Forest Technology Platform (Ministry of Economic Development of the Russian Federation, 2011). The technology platform "Bioindustry and Bioresources" (BioTech2030) was created to implement scientific, technical and innovative policies to spur the sustainable development of the bio-based industries. The basic technological spheres of interest of the platform are Industrial biotechnology, Agricultural biotechnology, Forest biotechnology, Food biotechnology, Aquaculture biotechnology, and Waste recycling/Eco-biotechnology. The expected results from BIO2020 are an increase in the biotechnology sector's contribution to GDP to a level of about 1 percent of GDP by 2020, reaching at least 3 percent of GDP by 2030 (Burghardt, Osmakova and Abramycheva, 2015; Leskinen *et al.*, 2020).

Focus of the bioeconomy in the Russian Federation

The bioeconomy concept adopted in the Russian Federation is mostly associated with biotechnology, while the Forest Scientific Council of the Russian Academy of Sciences has developed a broader definition, which also includes more traditional forest-based sub-sectors (Lukina, 2020). Specific sectoral policy gives impetus to wood-based construction (e.g. the Industry Development Strategy for construction materials for the period up to 2020 and beyond – perspective until 2030 (Government of the Russian Federation, 2016, 2019), raw material efficiency, or bioenergy production (e.g. Decree No. 1715-r on Approval of the "Energy Strategy of the Russian Federation for the period up to 2030" (Pristupa and Mol, 2015)).

10.9 Turkey

Bioeconomy-related efforts

The Ministry of Agriculture and Forestry took the first steps towards setting up a bioeconomy strategy in 2015, and again later in 2019 (Sürücü, 2019). This initiative, however, has not yet resulted in the establishment of a bioeconomy strategy for Turkey. The 11th (and most recent) National Development Plan emphasizes several issues related to the forest-based bioeconomy concept, including biotechnology, biodiversity conservation, sustainable forest management and contribution of forestry to the country's economy, support to rural development, increase of wood supply through plantations, and sustainability of ecosystem services (Presidency of the Republic of Turkey, 2019), and the report from the forestry thematic group mentions the sustainable bioeconomy (Ministry of Development, 2018). Although there are many aspects that fall within the concept of a forest-based bioeconomy, the term itself does not appear in existing National Development Plans.

In Turkey, forestry is not considered as an economic sector on its own, but it is included as a sub-group of the agricultural sector (Foresters' Association of Turkey, 2019). Since the adoption of the 2030 Agenda, Turkey has made an effort to implement and monitor the SDGs and their indicators by integrating them into the National Development Plans, as well as sectoral and thematic national policy and strategy documents (Government of Turkey, 2019).

Focus of the bioeconomy in Turkey

Turkey does not have a bioeconomy strategy in place. However, the term "bioeconomy" has been briefly described in the Biotechnology Strategy and Action Plan (2015–2018) by the Ministry of Industry and Technology. Increasing the level of technological knowledge and value-added production in the field of biotechnology, improving research, development and innovation ecosystem capacity, and manufacturing products with high added value and suitability for global competition are listed. The strategy covers biotechnology aspects related to health, agriculture and industry. The goals are as follows:

- To establish a health biotechnology sector that complies with legal regulations and ethical rules, with biotechnology to produce innovative products such as disease diagnosis, treatment methods, high value-added bioactive molecules, drugs, systems, tissues and organs.
- To use biological diversity resulting from the genetic resources of Turkey and recyclable resources effectively, developing and producing innovative products and to switch to an industrial structure developed towards "green" production.
- To develop biotechnological techniques and applications in the agricultural sector, taking into account environmental and human health risks, and effectively applying biosafety criteria.

10.10 United States of America

Bioeconomy-related efforts

The highest-level bioeconomy strategy is the National Bioeconomy Blueprint (The White House, 2012). The federal bioeconomy strategic objectives included a strengthening of research and development, fast-forwarding innovations from laboratory to market roll-out, reducing regulatory barriers, development of a bioeconomy workforce and the fostering of partnerships. The government of the United States of America continued to underline the importance of the bioeconomy by endorsing the strategic objectives as being of continued importance (The White House, 2019), however without putting forward a holistic strategy.

In addition to the bioeconomy strategy, several other relevant strategies and acts have been developed.Managed by the United States Department of Agriculture, the goal of the BioPreferred Program is to increase the purchase and use of bio-based products. The term "bio-based product" means a product determined by the Secretary to be a commercial or industrial product (other than food or feed) that is (i) composed, in whole or in significant part, of biological products, including renewable domestic agricultural materials, renewable chemicals, and forestry materials; or (ii) an intermediate ingredient or feedstock. The BioPreferred Program was created by the 2002 Farm Bill – the United States of America agricultural strategy document – and reauthorized and expanded as part of the Agriculture Improvement Act of 2018 (2018 Farm Bill). The Program's purpose is to spur economic development, create new jobs and provide new markets for farm commodities. The increased development, purchase, and use of bio-based products reduce the United States of America's reliance on petroleum, increases the use of renewable agricultural resources, and contributes to reducing adverse environmental and health impacts (USDA, 2020).

The Energy Policy Act was established in 2005 to address energy production in the United States of America, including "energy efficiency" and "renewable energy" as two of 12 headline categories. The Energy Policy Act included "grants to improve the commercial value of forest biomass for electric energy, useful heat, transportation fuels, and other commercial purposes" (House of Representatives, 2005).

The Farm Bill of 2014–2018 did not specifically relate to the bioeconomy but promoted key subsegments in the areas of agriculture, bioenergy and food (Dieckhoff P., El-Cichakli B. and Patermann, 2015). The subsequent Agricultural Improvement Act of 2018 (Public Law 115–334 of 20 December 2018) did, however, draw attention to components that are key in the development of the bioeconomy. The part on "timber innovation" calls for research and development to facilitate the use of innovative wood products, explicitly including cross-laminated timber, nail laminated timber, glue laminated timber, laminated strand lumber and laminated veneer lumber, in wood building construction in the United States of America (part III, sections 8641–8643). The Bill further gives attention to renewable energy including advanced biofuels, and manufacturing of renewable chemicals and bio-based products (Title IX - Energy). The Community Wood Energy and Wood Innovation Program of 2019 (United States Code, undated) is a grant scheme that resulted from the Agricultural Improvement Act and provides support for the development of community biomass-based heating and power plants, and for the development of innovative wood product facilities.

Focus of the bioeconomy in the United States of America

The United States of America bioeconomy is defined as an "economic activity that is driven by research and innovation in the life sciences and biotechnology, and that is enabled by technological advances in engineering and in computing and information sciences" (NASEM, 2020). This definition puts much emphasis on biotechnology. Forestry would currently not be included in the United States of America bioeconomy given that the extent to which biotechnology or the use of produced biomass for fermentation is used in relation to the industry in the country is not thought to be significant at this point. However, a recent report of the National Academies (NASEM, 2020) lays out a potential future for the use of biotechnology in promoting and protecting forest health, which would therefore make forestry an important contributor to the United States of America bioeconomy.

11 Appendix 2 - Selection of innovative wood-based products for this study

This section describes how the innovative forest products were selected from a vast pool of candidate products. Preference was given to products from the wood industry, manufactured from wood (e.g. solid pieces, wood chips, sawdust, etc.) or industrial side streams (such as black liquor and tall oil). The first step in selecting the forest products to be reviewed was to estimate how close the product was to entering the market. For this, we used the TRL (NASA, 2012; Table A2) as an indicator of the stage of development of the product or technology. Based on this classification, we estimated that products with low TRL (between 1 and 4) would take over 20 years to become commercially feasible, if they ever became technologically and financially viable. Medium to high TRLs (higher than 4) had the potential to enter the market in the next 5–20 years.

Table A2. The nine Technology Readiness Levels (TRL)

Level	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in an operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

To limit the range of possible products to be reviewed, the following specific criteria were used. Firstly, the raw material should be wood or by-products from the forest industry. Secondly, the selected products should have a TRL of 5–9, and an estimated potential to enter the market in the next 5–10 years. Novel products, which were already on the market, should have the potential to increase their market share. Thirdly, the products should have global significance, with similar products either manufactured or consumed in several regions of the world. The products should also cover a range of categories, namely: construction materials, bioplastics, wood-based composites, and wood-based textiles fibres. As long as these criteria were met, all types of products were considered, regardless of whether it was an intermediate or final product. A list of potential innovative products was built based on document analysis (scientific and grey literature), expert knowledge and a structured web search. Innovative products were also checked directly on websites of large companies. This latter search method, while not yielding a comprehensive list of products, was used to complement the list compiled with the methods previously described.

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