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Sustainable and circular bioeconomy in forest-based industries. How to get there.

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UNITED NATIONS

United Nations Economic Commission for Europe/
Food and Agriculture Organization of the United Nations

UNECE

ECE/TIM/DP/96

Forestry and Timber Section, Geneva, Switzerland

GENEVA TIMBER AND FOREST DISCUSSION PAPER 96

Sustainable and circular bioeconomy in forest-based industries

How to get there

UNITED NATIONS

Geneva, 2023

This work is co-published by the United Nations (UNECE) and FAO.

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Abstract

A sustainable and circular bioeconomy presents opportunities to improve climate change adaptation and resilience by promoting ecosystem restoration, nutrient and water retention in soils, supporting Indigenous People and local livelihoods based on biological products and services as well as building the conditions for more sustainably managed forests and fisheries. A transition to a sustainable and circular bioeconomy involves challenges and risks as well as benefits and opportunities. The potential trade-offs must be carefully considered and mitigating measures put in place to offset the negatives. Policy actions, partnerships and innovations are key tools to support a transition. While a transition to a sustainable and circular bioeconomy is a global goal, local production and consumption are key economic conditions to consider in achieving it. Local economies, green job opportunities and consumer interests should be supported and benefit from a transition.

Forest-based materials are used for a wide variety of products in a circular bioeconomy and innovation continues to refine existing and develop new applications. The considerations addressed in this study include the growing demand for renewable forest-based raw materials and energy as well as the drive for a reduction in global reliance on fossil fuels. Additionally, there are considerations for climate change, pollution, and waste, as well as the phasing out of single-use and fossil-plastics, that create opportunities and challenges for the forest sector. To further support a sustainable and circular

bioeconomy and the potential for a positive relationship with forests, public and private sector actors need to continue efforts that will effectively address the environmental, economic, and social aspects of a transition.

Acknowledgments

The Joint UNECE/FAO Forestry and Timber Section expresses its deep gratitude to everyone who contributed to this study.

The study is the result of a cooperative effort involving a network of authors, reviewers, editors, the UNECE/FAO Team of Specialists on Sustainable Forest Products, the FAO Advisory Committee on Sustainable Forest Industries, and a team of people working in the Forestry and Timber Section in Geneva and at FAO in Rome.

The Joint UNECE/FAO Forestry and Timber Section acknowledges the authors who wrote the chapters and, in so doing, shared their expertise and knowledge.

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The study also benefited greatly from the in-kind contribution to the publication by a number of experts who volunteered their time and expertise to provide information free of charge.

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Without the help of all these experts, it would not have been possible to produce this publication.

The project was managed by Alicja Kacprzak, at the Joint UNECE/FAO Forestry and Timber Section. The publication was reviewed at FAO by Ekrem Yazici, Sven Walter and Lyndall Bull, and at UNECE by Paola Deda, Liliana Annovazzi-Jakab and Roman Michalak.

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Contents

List of Figures

List of Tables

Executive Summary

The concepts of a sustainable economy, a low-carbon economy, a circular economy, and a bioeconomy are all complementary visions within an increasingly widespread sustainability trend. All of them concepts catalyse systemic change and provide answers to key economic, societal, and environmental challenges. These concepts offer answers to acute global challenges by balancing the use of natural resources with the climate and ecological stability for future generations.

The world's existing dominant economic models are based on the linear use of raw materials that drive escalating environmental, human health and social risks. There is a vital need to put in place an economic model for growth that is based on a regenerative design, such as is provided for by a circular bioeconomy. This transition requires an increase in the use of biodegradable, non-dangerous materials and the enhancement of design strategies to reduce waste.

A bioeconomy refers to the production and consumption of biomass-based goods, services and energy. It encompasses sectors such as forestry, pulp and paper production, agriculture, fisheries and the food industry. The vision for a bioeconomy entails a system where materials, chemicals and energy are based on renewable biological resources that allow economies to move away from fossil-based inputs. In contrast, a circular economy is focused on sustainable and resource-efficient processes.

A circular bioeconomy combines these visions and can be defined as the sum of all activities that transform biomass for use in different product streams, such as materials, chemicals, biofuels and food. This model allows communities and societies to reduce the environmental footprint of economic activities on ecosystems, human health and the planet overall.

A sustainable and circular bioeconomy presents opportunities to improve climate change adaptation and resilience by promoting ecosystem restoration, nutrient and water retention in soils, supporting Indigenous People and local livelihoods based on biological products and services as well as building the conditions for more sustainably managed forests and fisheries. A transition to a sustainable and circular bioeconomy involves challenges and risks as well as benefits and opportunities. The potential trade-offs must be carefully considered and mitigating measures put in place to offset the negatives. Policy actions, partnerships and innovations are key tools to support a transition. While a transition to a sustainable and circular bioeconomy is a global goal, local production and consumption are key economic conditions to consider in achieving it. Local economies, green job opportunities and consumer interests should be supported and benefit from a transition.

Forest-based materials are used for a wide variety of products in a circular bioeconomy and innovation continues to refine existing and develop new applications. Meeting the growing demand for forest biomass within a circular bioeconomy will require the balancing of natural ecosystem productivity, material efficiency and enhanced recovery, reuse, and recycling of materials at the end of life. Biomass has long been an essential renewable material for meeting global needs for food and nutrition, renewable energy, sustainable housing, and green building as well as other consumer goods for households and businesses. Biomass is a feedstock of choice for bioenergy, biomaterials, and a variety of substitutes for fossil-based goods. Biomass provides 25 percent of global material needs today while the remaining 75 percent is provided by non-renewable resources.

Protecting ecosystems' boundaries and supporting the full capacity of forests to contribute to a sustainable and circular bioeconomy requires an increased focus on and investment in forest ecosystem restoration, reforestation and afforestation while simultaneously addressing productivity on degraded lands, reduced loss and waste of materials and greater materials recovery. Forests have developed under the influence of historic climatic, ecological and economic patterns, including intentional cultural interactions, that have impacted the composition of forest ecosystems and their ecological response systems. Forests are increasingly impacted by changing climate, the variety of natural and anthropogenic pressures and thoughtful diversified management is necessary to defend against these threats and protect the regenerative and resilient capacity of forested ecosystems. There is a widespread need to manage forested land through restoration, protection, and stewardship activities at the local, regional, and global scale. Public and private owners, and local communities have an essential role in supporting forest ecosystem services through the thoughtful application of sustainable forest management (SFM), regenerative forest activities, landscape restoration and adaptive management. Some of the skillsets needed for a transition to a sustainable and circular bioeconomy include Indigenous Traditional Ecological Knowledge (ITEK) and the strengthening of relationships between ITEK and other research methods and scientific practices within academic institutions and between communities of practice. They are not key in the UNECE region. A circular bioeconomy could be an economy that is more directly connected to land management and the safeguarding of ecosystems, this could result in greater interest and investment in these landscapes and diverse ecological regions more generally.

The considerations addressed in this study include the growing demand for renewable and biobased raw materials and energy as well as the drive for a reduction in global reliance on fossil fuels. These trends contribute to pressures on forest ecosystems to provide biomaterials and the need to understand and address limitations to the sustainable provisioning of forest-based materials to ensure all forest ecosystem products and services remain available.

Additionally, there are considerations for climate change, pollution, and waste, as well as the phasing out of single-use and fossil-plastics, that create opportunities and challenges for the forest sector. To further support a sustainable and circular bioeconomy and the potential for a positive relationship with forests, public and private sector actors need to continue efforts that will effectively address the environmental, economic, and social aspects of a transition. This will include supply chains and organizational factors as well as policy and institutional drivers. There are many dimensions to consider within these conditions given the global abundance and diversity of forest ecosystem services, the variety of economic impacts from the sustainable production and consumption of forest-based materials and the vital societal and cultural importance of forests to people.

The development and value of this study are related to three interrelated considerations. The first consideration is that wood has unique and essential roles in a transition to a sustainable and circular bioeconomy because it is a renewable material with many natural and beneficial attributes. However, forest ecosystems are under pressure. As such, it is necessary to balance the provisioning of forest-based materials with the full range of ecosystem services and benefits they offer. Secondly, the study considers that there are limitations to material transformation and how materials are used in a circular bioeconomy. With careful design and development, renewable and biodegradable materials such as wood can be used in ways that make them increasingly available to recover for reuse or recycling at end-of-life. It is important for a transition to a sustainable and circular bioeconomy to ensure conditions for material recovery, renewability, biodegradability, and sustainability are maintained and enhanced for forest-based products. Finally, the third consideration of the study is the diversity of value chains and the impact of long-lived and short-lived product life cycles within a sustainable and circular bioeconomy. Maintaining and further developing long-lived value chains is essential to the reduction in waste generation within an economy and to support greater circularity. The principles of a circular economy are well aligned with common practices in the forest sector and the manufacturing of forest-based products. A transition to a circular bioeconomy provides the opportunity for business innovation, including new models, products, and services. The social impacts and potential outcomes of a transition to a sustainable and circular bioeconomy include the need for new skill sets across many workforces and employee development programmes, including training and educational curricula innovations.

The United Nations has recommended that a transition towards an economy based on renewable resources is needed to contribute to the objectives of the Paris Agreement and the Sustainable Development Goals (SDGs). Many actions have been undertaken to enable a transition to a sustainable and circular bioeconomy, including the European Union's (EU) Circular Economy Action Plan and the Biodiversity Strategy for 2030 within the European Green Deal. Almost 60 countries have already called for a paradigm shift from an economy based on fossil materials to an economy based on biological resources.

Cooperation and collaboration at the global scale are essential elements for the successful transition to a sustainable and circular bioeconomy. Resources that are essential to a circular bioeconomy are often available in the Global South and, may require support to promote innovations, technologies and investments to ensure the sustainable use of their resources. It is not necessarily true about wood. On the other hand. the Global North contributes to growing demand for products and materials, consequently, an alignment between supply and demand centres is an important condition for an effective transition to a sustainable and circular bioeconomy.

A circular bioeconomy represents an important opportunity for the regeneration of nature and biodiversity and, consequently, for forest ecosystems forest-based industries and the entire economy.

Chapter 1 Setting the stage

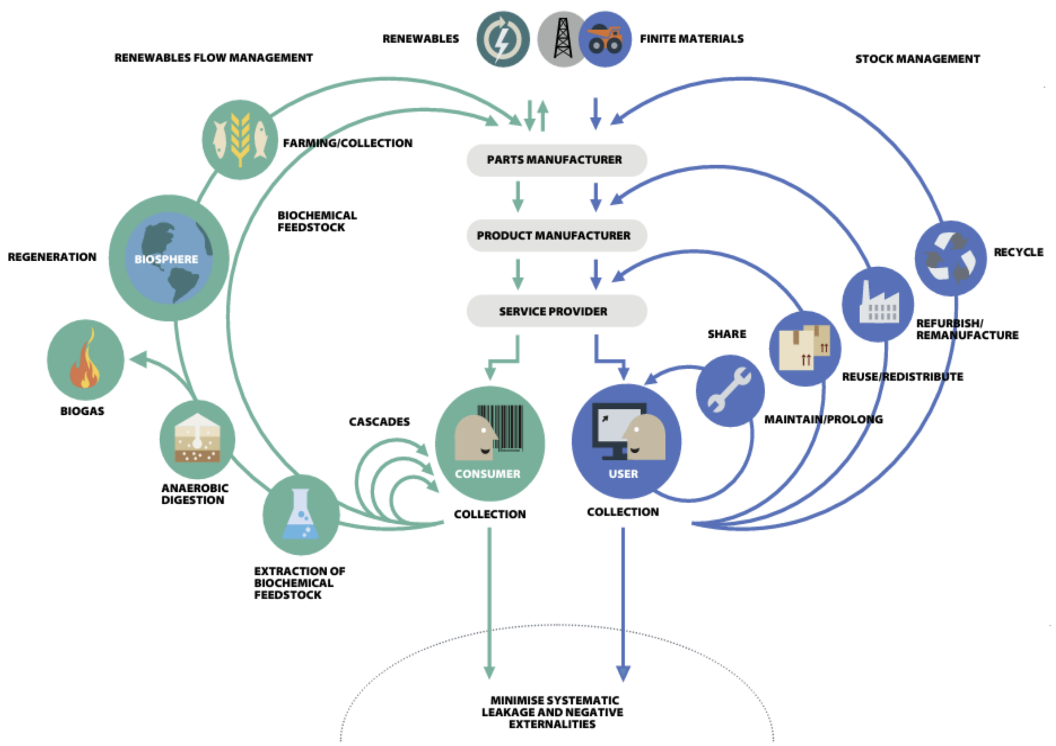
1.1. Understanding circularity and bioeconomy concepts

The concepts of a sustainable economy, a low-carbon economy, a circular economy, and a bioeconomy are all complementary visions within an increasingly widespread sustainability trend, aiming to avoid the depletion of natural resources and to maintain an ecological balance on the planet. These sustainability concepts are designed to catalyse systemic change and provide answers to key economic, societal, and environmental challenges faced by countries and economies alike. With the view of the conservation of natural resources, climate, biodiversity and ecological stability for future generations, these concepts are often seen as answers to acute global challenges such as overwhelming pollution, pressure on ecosystems and accelerating climate change. These challenges directly endanger life on the planet as it is known today. Furthermore, the ever-growing demand for raw materials has led to the unsustainable use of natural resources and unprecedented waste generation.

A **bioeconomy** refers to the production and consumption of biomass-based goods, services, and energy. It encompasses sectors such as forestry, pulp and paper production, agriculture, fisheries, and the food industry. It also covers parts of the chemical, pharmaceutical, biotechnological and energy industries as well as the manufacturing of cellulose-based textiles. The vision for a bioeconomy entails a system where materials, chemicals and energy are based on renewable biological resources that allow economies to move away from fossil-based inputs. In short, a bioeconomy is about breaking the dependence on non-renewable resources (UNECE/FAO, 2022).

Figure 1 Biological and technical cycle in a circular economy model by Ellen McArthur Foundation.

Biological and technical cycle in a circular economy model by the Ellen McArthur Foundation.

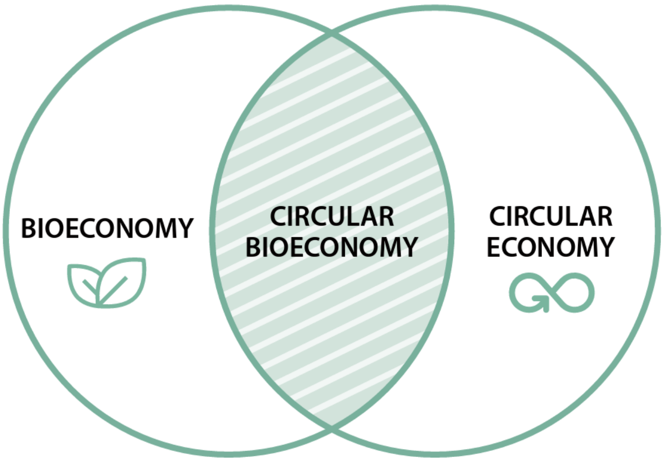


Source: https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic. Copyright © Ellen MacArthur Foundation (2017).

A circular economy refers to a wide range of materials and processes, both in the technical (blue) and biological (green) cycle of the economy (Figure 1 Biological and technical cycle in a circular economy model by Ellen McArthur Foundation.). An overlap exists between a circular economy and a bioeconomy. A circular economy is aimed at attaining sustainable and resource-efficient processes while a bioeconomy expands the possibilities to substitute fossil-based, non-renewable and non-biodegradable materials with renewable and biodegradable ones. The synergy of these two concepts (Figure 2 A Circular Bioeconomy Model) is expressed in the term circular bioeconomy, which can be defined as the sum of all activities that transform biomass for use in different product streams, including various materials, chemicals, biofuels and food (UNECE/FAO, 2022).

Figure 2 A Circular Bioeconomy Model

A circular bioeconomy.



Source: UNECE/FAO, adapted from Newton (2017).

According to the FAO, a bioeconomy is an economy based on the sustainable and circular use of biological resources and processes to produce food, feed and biobased products as well as services, an economic model that has major untapped potential to support both climate change mitigation and adaptation. A sustainable and circular bioeconomy also presents opportunities to improve climate change adaptation and resilience by promoting ecosystem restoration, biodiversity conservation as well as nutrient and water retention in soils. Furthermore, it would support Indigenous People and local livelihoods based on biological products and services while simultaneously building the conditions for more sustainably managed forests and fisheries. A transition to a sustainable and circular bioeconomy involves challenges and risks as well as benefits and opportunities. While the bioeconomy offers many potential solutions for climate action, any potential trade-offs involved in choosing one policy option over another (e.g. regarding land use, food security, human health and safety, etc.) should be carefully considered and mitigating measures put in place (Gomez *et al.*, 2022).

The existing dominant economic models around the world are based on the linear use of raw materials and cannot sustain current standards of living without escalating environmental, health and social risks. Changes in this unsustainable pattern can only be achieved through the process of putting into effect an economic model for growth that is based on a regenerative design, such as is provided for by a circular bioeconomy. Such a model allows communities and societies to maintain sufficient economic performance, and at the same time, reduce the environmental footprint on ecosystems, human health and the planet overall.

Consequently, the promotion of a sustainable and circular bioeconomy when technically possible, socially desirable and economically viable, is a way of reducing the catastrophic consequences of climate change, natural resources depletion and the biodiversity loss observed today. In addition, it is expected that a shift from the existing linear economic models which heavily depend on fossil raw materials and fuels, to low-carbon bioeconomies which rely more on biomass as a natural carbon sink, a sustainable raw material and a source of bioenergy allow for the mitigation of environmental challenges in the long-term.

The relationships between economy, nature and how different circular bioeconomy practices can benefit or damage the environment, have not been sufficiently explored, however, almost 60 countries have already called for a paradigm shift from economies based on fossil materials to economies based on biological resources (FAO, 2021).

The United Nations also recommends that a transition towards economies based on renewable resources is needed to contribute to both the objectives of the Paris Agreement and the Sustainable Development Goals (SDGs). When implemented with these prerogatives in mind, a circular bioeconomy can represent an important opportunity for the regeneration of nature and biodiversity, and consequently for forest ecosystems, human communities, and all forest-based industries.

1.2. Background and Objectives of the Study

This study aims to provide a comprehensive overview of a variety of factors which will have an impact on a successful transition of forest-based industries to a sustainable and circular bioeconomy, based on models presented in the previous section. The work on the study results from a mandate given by the Committee on Forests and the Forest Industry (COFFI) of the United Nations Economic Commission for Europe and the European Forestry Commission (EFC) of the Food and Agriculture Organization of the United Nations. During their Joint Session in November 2021, COFFI and EFC requested UNECE and FAO to "(a) prepare a series of studies further reviewing the application of circular models in specific forest-based industries, including through the identification of case studies and best practice, and (b) to take into consideration the whole forest-based value chain and bring attention to the circular nature of wood as a renewable resource and the role of sustainable forest management"[1].

The focus of the studies was identified through consultations with the UNECE/FAO Team of Specialists on Sustainable Forest Products and the FAO Advisory Committee on Sustainable Forest-Based Industries (ACSFI) between February and August 2023 and supported by the Joint UNECE/FAO Working Party on Forests Management, Economics and Statistics during its session in June 2023. The series includes the following studies:

- Sustainable and circular bioeconomy in forest-based industries. How to get there.
- Circularity concepts in the wood construction sector, as an example of a long-lived products value chain.
- Circularity concepts in the pulp and paper industry, as an example of a group of commodities with a short life span.

This study, as a part of this series, analyzes factors affecting the sustainable provision of forest biomass and general conditions of a successful transition towards a sustainable and circular bioeconomy in all forest-based industries. The focus here is placed on forests as the starting point of all value chains and

[1] (ECE/TIM/2021/2 FO: EFC/2021/2),
See also: E/ECE/1494 B (69) Circular economy and the sustainable use of natural resources; and E/ECE/1503 C (70) Promotion of Circular Economy and the sustainable use of natural resources.

operations rather than a detailed consideration of industry practices and value chains, which is the focus of the two other studies.

The series builds on the previous UNECE/FAO study 'Circularity concepts in forest-based industries' (2022) and aims to present a more detailed insight into the circularity issues in forest-based value chains. They are part of the research and guidance segment on policymaking of the UNECE/FAO Integrated Programme of Work 2022-2025, implemented by the UNECE/FAO Forestry and Timber Section in Geneva.

1.3. Scope and Limitations

This study provides context for understanding the opportunities and challenges that apply to forests and the forest sector related to a circular bioeconomy, resulting from the growing interest in forest-based materials that align with such an economy.

These considerations include the growing demands for renewable and biobased raw materials and energy coupled with the drive for a reduction in global reliance on fossil fuels. These demands contribute to pressures on forest ecosystems to provide biomaterials and the need to understand and address the limitations to the sustainable provisioning of forest-based materials to ensure all forest-ecosystem products and services remain available. Additionally, there are global-level considerations related to climate change, pollution, waste and addressing the phasing out of single-use and fossil-plastics that create opportunities and challenges for the forest sector. To further understand a sustainable and circular bioeconomy and its relationship with forests at that level, this study also addresses the general environmental, economic and social aspects of a transition. These aspects include supply chains and organizational factors as well as policy and institutional drivers.

There are many dimensions to consider given the global abundance and diversity of forest ecosystem services, the variety of economic impacts from the sustainable production and consumption of forest-based materials as well as the vital community and cultural importance of forests to people.

The development and value of this study are related to three interrelated considerations. The first consideration is that wood has unique and essential roles in a transition to a sustainable and circular bioeconomy because it is a renewable material with many natural and beneficial attributes. At the same time, forest ecosystems are under diverse pressures and it is necessary to balance the provisioning of forest-based materials with the full range of ecosystem services and benefits they offer. The second consideration is that there are limitations to material transformation and how materials can be used in a circular bioeconomy. With careful design and development, renewable and biodegradable materials such as wood can be used in ways that make them increasingly recoverable for reuse or recycling at end-of-life. It is important for a transition to a sustainable and circular bioeconomy to ensure that conditions for material recovery, renewability, biodegradability and sustainability are maintained and enhanced for forest-based products. Finally, the third consideration is the diversity of value chains and the impact of long-lived and short-lived systems within a sustainable and circular bioeconomy. Maintaining and further developing long-lived value chains is essential to the reduction in waste generation within the economy and to support greater circularity.

Many actions have already been undertaken to enable a transition to a sustainable and circular bioeconomy, including the EU's Circular Economy Action Plan and the Biodiversity Strategy for 2030 within the European Green Deal. The implementation of a circular bioeconomy and the protection of biodiversity are deeply connected. The International Union for Conservation of Nature (IUCN) recently reported on the underexplored relationship between a circular economy and biodiversity and concluded that the forestry sector has the potential to provide significant benefits to nature if it achieves greater circularity (Oberč, 2022). Strategies to realize these benefits include further embedding nature within core definitions for a circular bioeconomy as well as utilizing nature-based solutions to achieve desired environmental and economic outcomes while expanding the natural capital concept and mechanisms for sustainable finance (Oberč, 2022). The European Environment Agency (EEA) has also identified three areas where a circular economy can benefit biodiversity. These areas include reducing primary resource demand through increasing efficiency in material use and circularity; preventing pollution and reducing the use of hazardous substances; and, finally, the expanded practice of biodiversity-friendly sourcing that avoids harm to natural systems and promotes regenerative practices (EEA, 2023).

Furthermore, modelling research methodologies provide scenarios for halting biodiversity loss through a transition to a circular bioeconomy, including opportunities to recover biodiversity to 2000 levels by 2035. This research also examined the potential to avoid negative impacts on 280 million hectares of natural forest by 2050 through changes to the four economic sectors; food and agriculture; fibres and textiles; buildings and construction; and forests (Sitra, 2022). Strategies for improving circularity in the forest sector include extending the useful life of products, enabling material reuse in ways that reduce reliance on the generation of new wood and sourcing new wood from forests that are managed to improve biodiversity outcomes (Sitra, 2022). These strategies have direct policy implications and relevance to public and private-sector leadership in supporting a transition to a sustainable and circular bioeconomy.

1.4. Methods and Data Sources

The evidence and information reviewed in this study come primarily from desk research, a review of relevant scientific literature and the authors' subject matter knowledge. Additional information has been provided from industry documentation and interactions with industry experts, government information sources as well as documented case studies and examples of good practice.

1.5. Structure of the study

Chapter 1 sets out the context and the objectives of the study and provides information on what is the understanding of a sustainable and circular bioeconomy for the needs of this study.

Chapter 2 details opportunities and challenges for the forest sector resulting from a growing interest in a sustainable and circular bioeconomy.

Chapter 3 examines the general conditions required for a successful transition to a sustainable and circular bioeconomy in forest-based value chains.

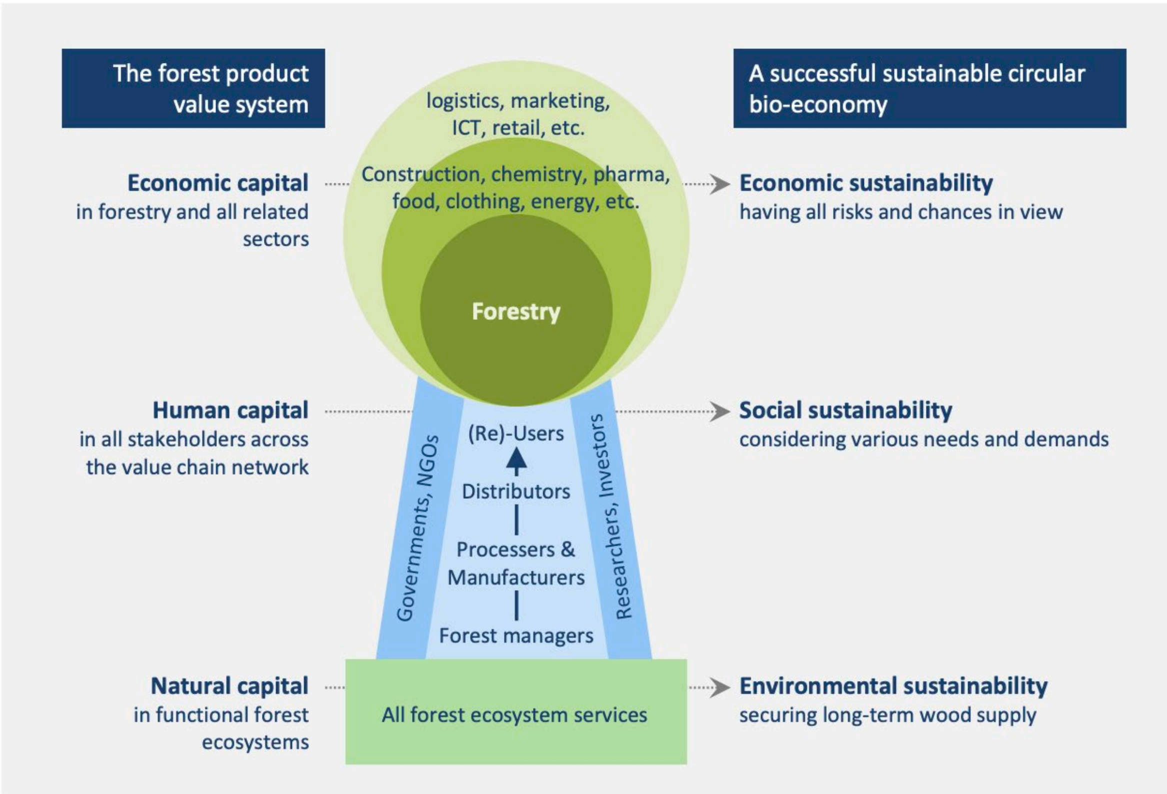
Chapter 4 provides conclusions to the study.

Chapter 2 Factors affecting the demand and the sustainable provision of forest biomass

Forest resources produce a variety of biobased material alternatives for fossil-based materials that have applications in many sectors of the economy, ranging from construction, furniture manufacturing, packaging, textiles, pharmaceuticals, automotive and space industries through to the provision of nourishment and other necessities of life. Sustainable forest management, wood processing, recycling and disposal result in forest biomass that is suitable for energy needs, reducing the demand for fossil fuels. As such, forest-based materials will benefit the forward-looking paradigm shift to an economy based on the circularity of biological resources. The significant scale of benefit for entire economies is possible because forests provide raw materials for many value chains and can thus prompt a transition in multiple strategic sectors with high carbon impacts. For that reason, there is a growing demand for forest-based materials.

A recent dialogue process initiated by the Federal Ministry of Food and Agriculture (BMEL) of Germany identified four characteristics of a transition towards a sustainable circular bioeconomy. These four characteristics entail changes to production and consumption systems to increase resilience; technological innovations for a cascading use of resources; social innovations that address the entire forest product value system; and varied pathways that acknowledge complexity and are driven by evolving values (Schmitz, 2023). As shown in Figure 3 System-Wide View of the Forest Product Value System in a Circular Economy, a transition to a sustainable and circular bioeconomy requires holistic system thinking across the entire forest product value system.

Figure 3 System-Wide View of the Forest Product Value System in a Circular Economy



Note: ICT: Information and Communication Technology.

Source: (Schmitz, 2023)

This growing demand for forest biomass represents a number of opportunities but also challenges for the sector. The challenges are broadly associated with ecological, economic and social capacities for meeting the rising demand for forest resources and biomass while ensuring the sustainability of supply in the context of increasing pressures on ecosystems. These pressures result from climate change, wildfires, pest and disease outbreaks as well as landscape use priorities, which can all impact the regeneration processes of forest resources and the resilience of forest ecosystems, affecting productive capacity.

Meeting the supply demand for forest biomass and a transition to a sustainable and circular bioeconomy can and should also be addressed through material recovery, including the collection of wood, paper and other forest-based products for reuse, recycling or energy recovery at the end of live. However, this is hampered because the recovery rate of secondary raw materials from post-consumer residues is still low due to limited economic viability and underdeveloped waste collection infrastructure. Consequently, it is important to analyse how these factors are impacting and will continue to impact forests, forestry and different forest-based industries. The following sections will evaluate if the ongoing shift towards a sustainable and circular bioeconomy will alleviate or exacerbate existing challenges and opportunities.

2.1. Growing demand for raw materials

The global demand for raw materials continues to grow. During the 20th century, global material use rose at about twice the rate of population growth (PACE, 2019). In some cases, rates of increase in resource extraction were many times greater than population growth. Analysis of global consumption shows a massive increase in annual materials extraction from 22 billion tonnes in 1970 to 70 billion tonnes in 2010 and a comparable acceleration in material extraction since 2000 (Schandl *et al.,* 2017). The Organisation for Economic Cooperation and Development (OECD) reported further growth in the global use of material resources to 89 billion tons (Gt[2]) in 2017 (OECD, 2019).

Global material use has accelerated even as economic and population growth have slowed. Between 1970 and 2010, the global economy expanded more than threefold, the global population almost doubled, yet global material extraction tripled (UNEP, 2016). Global material use increased from 7 tonnes per capita in 1970 to 10 tonnes per capita in 2010, indicating an increase in the material standard of living in many parts of the world (UNEP, 2016). As a result, material extraction has grown in all regions of the world in response to increased demand.

Another observation of the period from 1970 to 2019 was made using the Global Material Flows Database of the UN International Resource Panel developed in the context of a project funded by the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology in Austria (MaterialFlows.net, 2021). This observation led to the conclusion that during that period, global material consumption increased remarkably among all raw materials categorized as metals, fossil fuels, non-metallic minerals and biomass.

[2] Gross register tonnage or gross tonnage (GT) represents the total internal volume of cargo vessels. 1 GRT = 100 cubic feet ≈ 2.83 cubic metres.

Exceptional growth in extraction has occurred among non-renewable materials, including a 365 percent increase in industrial and construction-related minerals since 1970 (MaterialFlows.net, 2021). This growth is related to the central role these minerals have in meeting the demand for ongoing infrastructure improvements in energy, transport and construction work globally. Their associated growth rates indicate the continued importance of such industrial development, especially in emerging economies. Consumption of fossil fuels has also experienced growth of more than 159 percent since 1970 in response to rising energy demands due to intensified manufacturing processes. Also, the demand for metals, more than tripled between 1970 and 2019. The extraction of renewable resources and biomass has also grown since 1970; however, the rate of increase is lower at 105 percent (MaterialFlows.net, 2021). Nonetheless, it is important to mention that increased demand for biomass-based energy production and renewable resources from agriculture and forestry to support a transition to a sustainable and circular bioeconomy will need to be balanced with the productive capacity of natural systems.

Trends in global material extraction growth are also influenced by growing wealth, consumption and international trade (Schandl *et al.,* 2017). The global gross domestic product (GDP) is projected to more than triple between 2017 and 2060 and average per capita income may reach USD 37 000 by 2060 (OECD, 2019). The "Global Material Resources Outlook to 2060" estimates that global materials use could rise from 89 billion tonnes in 2017 to 167 billion tonnes in 2060 under existing policies (OECD, 2019). The projected growth is across all major categories of materials, as shown (Table 1), which highlights that growth in biomass use is expected to exceed growth in fossil fuel use but where growth in the extraction of metals and non-metallic minerals will be the highest. This global materials-use scenario through 2060 could result in a doubling of greenhouse gas (GHG) emissions, greater pollution of soil, water and air as well as toxic effects on humans and ecosystems that will hurt economies and societies (OECD, 2019).

Table 1 Global Materials Use Projected to 2060

Material Category	Global Use in 2017 (billions of tonnes)	Global Use Project to 2060 in the absence of new policies (billions of tonnes)	Growth (%)
Metallic Ores	9	20	122
Fossil Fuels	15	24	60
Non-metallic Minerals	44	86	95
Biomass	22	37	68

Source: OECD, 2019.

Greater materials intensity in production and consumption, the growing share of services in the economy and technological developments that decouple growth from material inputs all contribute to improving material use levels and trends (OECD, 2019). Therefore, actions and policies that support a transition to a sustainable and circular bioeconomy can reduce the negative impacts associated with global materials use and help countries and economies change course.

According to the UN International Resources Panel (2020), resource extraction and processing account for more than 90 percent of global biodiversity loss and water stress as well as approximately 50 percent of global GHG emissions. Emissions from the production of materials as a share of global GHGs increased from 15 percent in 1995 to 23 percent in 2015. Although this can be compared to the share of GHG emissions from agriculture, forestry and land use change combined, they have received much less attention. An estimated 80 percent of emissions from material production were associated with material use in construction, understood as solid materials including metals, wood, construction minerals and plastics as well as manufactured goods. Fuel, food and chemicals are not included.

2.1.1. Biomass demand

The trend toward sustainability is driven by the need to address resource constraints related to climate, water, energy and land, as well as by advances in microbiology and shifts in consumer preferences (von Braun, 2018). Therefore, biomass, forest biomass and growing applications for these renewable materials in a sustainable and circular bioeconomy provide opportunities and challenges related to the growing demand for raw materials.

Wood, as a key renewable resource, can be used for creating biodegradable and recyclable materials. Production residues from the forest industry and primary manufacturing processes can be reused in cascading systems that result in minimum waste. These practices have resulted in nearly complete utilization of wood in production processes and very little pre-consumer waste generation. There has also been significant development of post-consumer waste recovery and recycling systems, especially for paper and packaging materials. When discussing the role of wood in a sustainable and circular bioeconomy, it is important to acknowledge that wood fibre recycling currently faces inherent limitations in the number of possible reuse cycles, however, this limitation is being studied and solutions may be possible through greater use of nanotechnology to improve recycling outcomes (Rahmaninia, 2015).

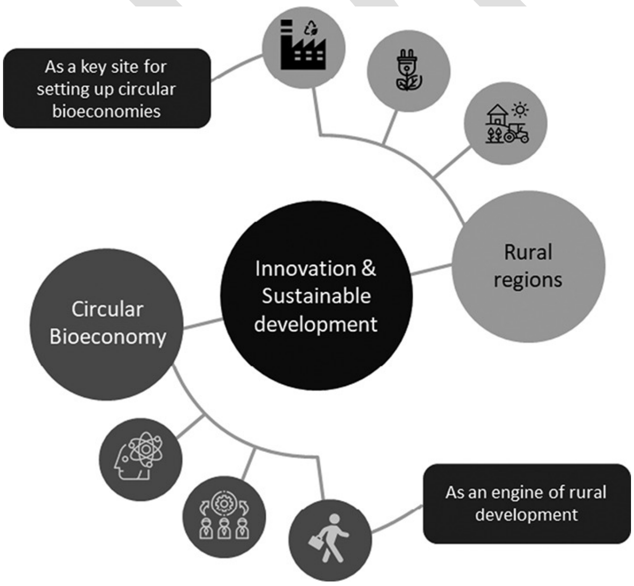
All forest-based products are biobased and are, therefore, both renewable and naturally compostable if properly designed. However, natural decomposition of materials should generally be minimized as there needs to be a strong focus on the collection and recycling of materials. Wood has great enduring value as a renewable material as almost all its production side streams can become raw materials for other streams, even sawdust has many possibilities for use and reuse. These materials may be utilized in value-added products and materials (i.e. particle board and packaging), innovative materials (i.e. cellulose-based insulation) and renewable energy production. This material efficiency is widely recognized and has been employed in forest-based industries for many generations. These material-use practices meet the goals of circularity and contribute significantly to the improvement of value and supply chains, a step that is necessary to expand a sustainable and circular bioeconomy. Meeting the growing demand for forest biomass will require the balancing of natural ecosystem productivity, material efficiency, enhanced recovery and reuse as well as the recycling of materials at the end of life.

In 2018, the global production of and trade in major wood products, such as industrial roundwood, sawnwood and wood-based panels, surged to their highest level since FAO began recording forest statistics in 1947 (FAO, 2019). In 2018, the value of international trade in wood products was 11 percent higher than in 2017 with the fastest growth occurring in North America, Europe and the Asian-Pacific region (FAO, 2019). In 2018, FAO reported that the consumption of post-consumer recovered wood exceeded 27 million tonnes. From 1980 to 2020, it is estimated that the production of recovered paper increased by 352 percent, including a 59 percent rise since 2000 (FAO, 2021).

Forest-based materials can be used for a wide variety of products in a circular bioeconomy as innovation continues to develop new and expanded applications. The bioscience industry is currently engaged in the development of biobased fuels, chemicals and other industrial products and by-products. These efforts are designed to help address climate change and reduce dependence on fossil-based and non-renewable raw materials currently being relied upon for the production of these products. For example, by-products from industrial processes, such as lignin, have huge potential to add value to new products to meet the demand for sustainable raw materials in several industrial sectors. These innovations can result in significant new investment, economic growth and job creation. For example, since 2018, the bioscience industry in the United States of America has seen job growth of 7.2 percent, which is more than twice the overall growth rate for the private sector (BIO, 2022). Furthermore, bioscience is recognized for providing jobs with wages that are nearly twice the overall average for the nation’s private sector (BIO, 2022).

The increased use of biomass is likely to impact various segments of society in both positive and negative ways. Policy actions, partnerships and innovations can contribute to mitigating or avoiding the negative aspects of these impacts. One recognized concern for a potential negative impact is on food security and natural resource protection if there is increased competition between land uses for fibre and biomass production rather than food production and ecological protection. It has also been suggested that the increased demand for biomass has the potential to create economic growth and opportunity in rural areas where forest biomass feedstocks are anticipated to be produced and where investments may occur to support these new processes and manufacturing. As illustrated in Figure 4 Rural Areas as Strategic Locations for Circular Bioeconomy-Related Activities, rural areas could be key locations for establishing industries and production capacity to support a transition towards a sustainable and circular bioeconomy while innovations and sustainable development may lead entrepreneurs and investors to seek collaboration in rural regions, especially if barriers related to innovation, education and partnerships can be addressed (Brandão, A.S., 2022).

Figure 4 Rural Areas as Strategic Locations for Circular Bioeconomy-Related Activities



Source: (Brandão, A.S., 2022)

The impacts of investment in a sustainable and circular bioeconomy will also likely be felt in urban and suburban areas with changes to material handling systems, expanded material reuse and recovery as well as changes in consumer behaviour to support greater circularity.

The increased use of biomass as a critical raw material for a sustainable and circular bioeconomy may necessitate decentralization of production, processing and manufacturing across geographic areas in efforts to increase efficiency and reduce costs associated with harvest and transportation. Similarly, increased use of biomass for energy production, including both electricity and thermal, may contribute to the reduction of the international trade of fossil fuel resources. A sustainable and circular bioeconomy should be an economy that is more directly connected to the management of land and safeguarding of ecosystems which could result in greater interest and investment in these landscapes and diverse ecological regions more generally.

In the context of increasing demand for raw materials and forest-based products, there is a need for coordination between the biological cycle of forests and the technical cycle of forest-based industries in a circular economy. This coordination exists to some degree in current markets and supply chains but will need to be strengthened to maximize circularity along the various value chains.

2.2. Growing demand for energy and the phasing out of fossil fuels

The demand for energy is growing in all sectors of the economy and most of the global population still depends on fossil fuels to meet their needs. Coal, gas and oil meet 75 percent of global heat demand (IEA, 2021). Renewable energy has been growing significantly in recent decades, yet its share of total energy consumption remains relatively steady because total global energy consumption continues to grow at a similar rate (IEA, 2021). Renewable energy represented approximately 25 percent of the electricity sector in 2018, while its share in the heat and transport sectors has been much slower (IEA, 2023).

Sub-Saharan Africa has the largest share of renewables in its energy supply, including 85 percent biomass energy (IEA, 2021). Latin America and the Caribbean also have large renewable energy shares, derived from hydropower for electricity, bioenergy for industrial processes and biofuels for transport (IEA, 2021). The global share of total final energy consumption (TFEC) provided by renewables was 18 percent in 2019 but needs to reach over 30 percent by 2030 to be on track to achieve net-zero energy emissions by 2050 (IEA, 2022).

Heating and cooking are the dominant uses of wood in many areas of the world. They account for about 50 percent of global wood consumption and 33 percent of the renewable energy used in the world (FAO, 2021). Between 2010 and 2020, access to clean cooking fuels and related technologies increased by a further 12 percent, making them available to 69 percent of the world’s population; however, at current rates, only 76 percent of the world’s population will gain access by 2030 (Grima, 2023).

Transitions in the energy sector are essential to addressing climate change and supporting a sustainable and circular bioeconomy. Despite significant progress on SDG 7, Affordable and Clean Energy, more work is needed to address demand and sources of energy, including the need to phase out fossil fuels. Wood and biomass energy supply as much renewable energy globally today as solar, hydroelectric and wind power combined (IEA, 2022; Grima, 2023).

Globally, more than one billion people gained access to electricity from 2010 to 2019, however, basic electricity services became unaffordable for 30 million people (IEA, 2021). The situation regarding affordable electricity worsened as a result of the COVID-19 pandemic with nearly 90 million people in Asia and Africa no longer able to afford their basic energy needs (IEA, 2022). As of 2022, 733 million people, less than 10 percent of the global population, do not have access to electricity, which is down from 1.2 billion in 2010 (IEA, 2022).

The International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) consider bioenergy as a central element to achieving Net Zero Growth and fulfilling the Paris Agreement (FAO, 2021). The climate change mitigation scenarios evaluated by the IPCC include the use of bioenergy and the development of bioenergy with carbon capture and storage (BECCS) as a technology to support net negative emissions. The technology of BECCS combines the production of renewable biomass energy (i.e. a power plant utilizing wood pellets) with carbon capture and storage at the emissions site through mechanical or chemical removal methods. Biomass energy and biofuels provide electricity generation as well as renewable thermal heat required for many manufacturing processes. In these scenarios, the forest sector contributes to industrial decarbonization by providing low-carbon fuels, feedstocks and energy sources (LCFFES).

Evaluations show that the potential for these technologies to provide climate change mitigation is significant, but care must be taken to balance land use competition and any stress placed on soils, food production, water resources and other conditions. The scale of bioenergy and BECCS development is a key consideration in balancing the associated impacts. The scenarios also recognized that large-scale bioenergy developments can provide potential ecological benefits, for example, by expanding the use of continuous cover and perennial cropping systems in agricultural diversification and alternative production models. Strategies to accomplish carbon dioxide removal (CDR) include bioenergy and BECCS as well as reforestation and afforestation activities. The IPCC acknowledges that these strategies can compensate for emissions in other sectors that are difficult to eliminate and there is an urgency to the situation because delaying action will result in larger needs for technology deployment in the future (Pitti *et al.,* 2019).

In collaboration with its partners, FAO developed the Support Package to Decision-Making for Sustainable Bioenergy that includes the Bioenergy and Food Security (BEFS) Approach of FAO (FAO, 2014) and the Global Bioenergy Partnership (GBEP) Sustainability Indicators (GBEP, 2011). These tools can contribute to the sustainable use of bioenergy amid increasing demand for forest-based resources as fossil fuels are expected to be phased out.

2.3. Pressure on ecosystems

Forests provide many essential ecosystem services. These services can be categorized into four types, namely (i) provisioning services, such as for food, raw materials, water and medicines; (ii) regulating services, such as carbon sequestration and water cycling; (iii) cultural services for recreation, human health, tourism and spiritual experiences; and, finally, (iv) supporting services for preserving biodiversity and overall ecological function (Bolte *et al.,* 2023). These ecosystem services need to be balanced to ensure that they remain available to future generations to utilize in ways that meet their needs.

Biomass has long been an essential renewable material for meeting the world's need for food and is increasingly used as a feedstock of choice for bioenergy, biomaterials and a variety of substitutes for fossil-based goods. As the demand for biomass continues to rise and its uses are diversified, it is important to analyze conditions for the sustainable provision of forest-based materials.

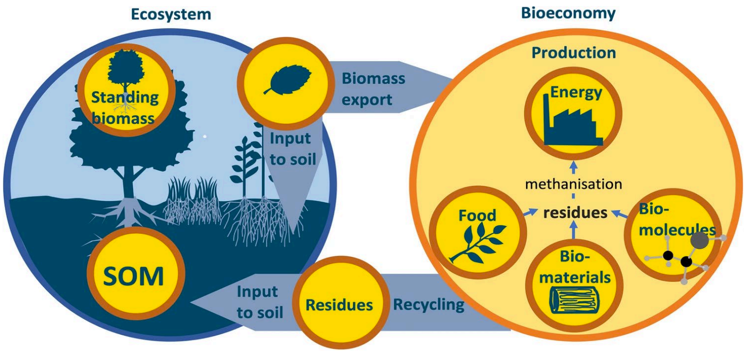
Since 1970, global biomass utilization has risen from 9 billion tonnes to 22 billion tonnes in 2017 and is expected to reach 37 billion tonnes by 2060 (OECD, 2019). While global production of roundwood has risen by 12 percent in the last twenty years (FAO, 2022), biomass still provides only 25 percent of global material needs today, with the remaining 75 percent provided by non-renewable resources. Biomass includes a wide variety of organic materials derived from forests, agriculture and other natural resources, albeit with most coming from agriculture industries or the forest sector.

Biomass, including forest-based biomass, can be used for a diverse array of products and materials. For example, it contributes to meeting global needs for food and nutrition, renewable energy, sustainable housing and green building as well as other consumer goods for households and business operations. The global need to utilize biomass as a raw material in products is expected to continue to grow, including growth associated with greater development of a sustainable and circular bioeconomy.

The key determinant of the overall demand for forest-based biomass is the demand for wood as a construction material. Lumber and other construction materials, including engineered wood and mass timber products, are of higher value than when wood is used in energy, packaging or paper production. The demand for wood use in the built environment generates residues and manufacturing by-products that are utilized in the production of other products and used to generate bioenergy. Estimates suggest that by 2030, demand for wood in the built environment may triple and packaging demand will double (FAO, 2022).

The increased reliance on biomass and forest-based materials is a positive trend that supports a transition to a sustainable and circular bioeconomy, away from a fossil-based economy. However, the trend should be encouraged only within the ecosystem's boundaries and sustainability. Many of the world's forests and forest ecosystems already face ecological pressures that limit their sustainable provisioning of materials. Ecological pressures include raw material use, greenhouse gas emissions, acidifying air emissions, and air pollutants leading to harmful ground-level ozone. Therefore, continued growth in the demand for forest-based materials will need to balance expanded extraction with the restoration of degraded lands, conservation areas and improved SFM strategies. The expanded and sustainable use of biomass contributes to feedback loops between the above and below-ground components of ecosystems and the expanded circular bioeconomy. Exports to food, bioenergy, biomaterial and biomolecule sectors, return to the soil (soil organic matter or standing biomass (Figure 5).

Figure 5 Biomass fluxes among ecosystems and a bioeconomy



Source: (Derrien, Barré, Basile-Doelsch *et al.,* 2023) https://link.springer.com/article/10.1007/s13593-023-00876-x/figures/9 (permission to be asked)

Respecting ecosystems' boundaries and supporting the full capacity of forests to contribute to a sustainable and circular bioeconomy requires increased focus and investment in forest ecosystem restoration, reforestation and afforestation that addresses productivity on degraded lands, reduced loss and waste of materials as well as greater materials recovery. All actors in both the public and private sectors have a role to play in making these changes scale up.

2.4. Crop Productivity and Material Efficiency

Meeting the growing demands for raw materials without crossing ecosystems' boundaries requires the growth of supply through greater productivity. Increased biomass supplies can be gained through an intensification of production and harvesting (i.e. more volume per hectare),increasing the area of productive land utilized for agriculture and forestry and activation of not used managed forests. Both strategies to increase biomass productivity have environmental, social and economic impacts to consider. The outcomes can be negative if productivity is not balanced with continuing to provide the full spectrum of forest-ecosystem services. For example, the intensification of production can lead to biodiversity loss if natural systems are converted to simplified models of production or if extraction exceeds regenerative capacities. Similarly, the expansion of agricultural production can come at the cost of forest ecosystems when land use change occurs. These environmental impacts can drive economic losses as well if industries such as tourism are harmed and social concerns arise when traditional and cultural ecosystem services are diminished by a narrow focus on greater biomass productivity.

According to FAO, sustainable crop production intensification (SCPI) aims to produce more from the same area of land while reducing negative environmental impacts, conserving natural resources and enhancing healthy ecosystem services. This approach can be applied in all types of forests (planted, tropical, temperate and boreal) regardless of size or geographic region and includes different techniques that can be used together or individually. With investments in research and innovation, current practices can be adjusted and new strategies developed to meet the challenge that needs addressing.

Biomass and biomaterial supplies can also be increased in conjunction with ecosystem restoration and biodiversity protection goals that reduce current ecosystem pressures. For example, biomass production could include greater use of perennial cropping systems, agroforestry and integrations between agriculture and forestry that have lower impacts than current unsustainable production models. Greater expansion of land use to support the growth of forest-based products can provide co-benefits for wildlife habitat and water resource protections. A recommended approach for achieving these types of positive outcomes is for decision-makers to embrace complexity by promoting the integration of different sectors to create effective solutions and to take the time to establish localized approaches that address inequalities as well as social and economic heterogeneity (Grima, 2023).

Reducing the risk of negative environmental impacts to forests as a result of rising global demand for biomass can also be achieved through an increased focus on material use efficiency and the minimization of wood loss and waste in supply chains from harvesting to end of use. This focus is essential to a successful transition to a sustainable and circular bioeconomy. Many efforts are already underway to remove waste and loss from forest and wood product manufacturing systems. For example, wood utilization rates in Canada improved from 61 percent recovery in 1970 to 83 percent in 2016 and residues from lumber products are utilized in other products or for bioenergy production (FAO, 2022).

Through SFM, policy- and decision-makers, owners and forest managers ensure the production of ecosystem services that meet the needs of people today while also protecting the interests and needs of people in the future. Analysis, management and monitoring of forest resources allow forest management to balance, protect ecosystem functions while providing for the prediction and projection of the sustainable supply of forest-based materials. These gains are potentially significant when forest managers can reduce or avoid supply loss due to destructive events such as wildfires. The forecasting of timber availability related to wildfire impacts and harvesting levels is becoming more important in the decision-making process in many regions, including in the planning of forest strategies and future investments (Rego, 2013). Increased demand for biomass could support improved forest sustainability in some regions.

For example, in California, the United States, research found that increased demand for wood residues could support forest health treatments resulting in up to 7.3 million dry tonnes per year of removed waste. This would provide up to 17 million tonnes of carbon dioxide equivalent climate benefit and reduce the wildfire hazard on nearly 5 million hectares (Cabiyo, 2021).

Sustainable provisioning of forest-based materials without compromising other forest ecosystem services can also be accomplished through a cascading use of wood raw materials. The impacts can be estimated through material balances that approximate material losses by estimating the difference between the quantity of material consumed in one processing step and the total material produced in the following processing step. The path of cascading use and the range of estimated losses contribute to identifying where and how efficiency may be gained. In the case of sawnwood production, reporting countries indicate that 45 to 66 percent of the roundwood volume used becomes sawnwood, some 33 percent becomes chips and slabs, approximately 10 percent becomes sawdust and, in some countries, an additional 2 to 10 percent becomes shavings (FAO, 2022). What is not used for any of the above products is considered shrinkage loss, which varies considerably between countries due to factors such as differences in tree species, the portfolio of products produced, available markets and technologies employed.

The provisioning of forest-based materials without compromising other forest ecosystem services should target all stages of a material's lifecycle, namely extraction, transport, manufacturing, consumption, recycling and disposal. However, one of the main challenges to integrated lifecycle approaches is that material lifecycles and their impacts often involve a multitude of actors and extend across political and geographic boundaries. Strengthened policy coherence, together with increased coordination among all relevant stakeholders can effectively counterbalance the increasing fragmentation of global supply chains. Some good practices have already been established in the pulp and paper industry as well as for wood construction.

Paper is already a widely and commonly recycled material around the world. The pulp and paper industry has achieved a recovery rate of more than 60 percent in Europe and North America; nearly 50 percent in Latin America, the Caribbean, Asia and the Pacific; and nearly 30 percent in Africa (FAO, 2022). There are technical limits to paper recycling in terms of the materials that can be recovered and how these can be repurposed because, for example, some paper and packaging materials associated with food service, medical and hygienic uses are not suitable for recovery and reuse. It is estimated that achieving the maximum recycling potential for wood and paper could improve the wood-use efficiency in the European forest industry by more than 30 percent and provide a 52 percent reduction in GHG emissions (FAO, 2022). The feasibility and associated benefits of enhanced recycling vary by region and there are technical barriers to maximizing material recovery as well as the need for expanded supportive policy frameworks.

Recycling of solid wood products is common in many countries where it is most used for energy generation, particleboard manufacture, animal bedding or landscape uses. As such, there is a need to generate higher-value products and encourage higher rates of recovery and reuse (Irle, 2019).

Although wood use in construction offers substantial sustainability and circularity benefits, additional innovation is still needed. Currently, waste from building deconstruction and demolition is not being recovered effectively. Designing for building adaptability, disassembly and effective material recovery needs to be undertaken to improve the circularity of wood in the construction sector. The data suggests that there is considerable room for improvement in the treatment of wood-resource recycling at the end of life for buildings. The greatest opportunity for improved circularity for wood in this context is in the recovery and reuse or recycling of building demolition waste.

Building deconstruction and effective wood recovery from the built environment is challenging because of a number of existing conditions in the marketplace. Current conditions make waste disposal relatively cheap in many regions and open burning of wood waste is frequently permitted as a disposal option. Growing demand for wood for energy generation also presents a challenge to higher valued uses. Another factor is that deconstruction is difficult, especially since buildings have not been constructed with dismantling in mind. Buildings have mainly been designed with performance, customer satisfaction and durability as objectives, with only a very small percentage of existing buildings being fully demountable. Additional problems to consider are that older buildings may contain materials that are today recognized as environmental hazards; structural components are penetrated by electrical, plumbing as well as heating, ventilation and air conditioning (HVAC) systems. Furthermore, construction adhesives and other fasteners make the separation of components physically challenging and may result in damage to materials when deconstruction is attempted.

Policy changes, construction innovations, design improvements and other actions to support expanded material recovery and reuse are needed as well as leadership from engineers, architects and design professionals to enhance greater circularity and recovery of biobased materials.

In general, the world's forests can continue to support increased demand for forest-based materials if they are managed sustainably. This requires market actors, governments and advocacy groups to establish and enforce systems that ensure products are legal and not produced in ways that contribute to deforestation for forest degradation. In this context, government policies provide the key framework for ensuring the legal and sustainable trade in forest-based materials.

The forest sector's leadership on responsible supply-chain management is also needed. This would create an opportunity to promote the sector and ensure the sustainable, legal supply of wood fibre and provide the potential for traditional as well as innovative wood and paper products to contribute to increased sustainability and circularity of forest-based materials. In turn, this allows the promotion of the renewability and sustainability characteristics of wood and its availability through the certification of sustainability and legality, both of which contribute to maintaining and growing market demand.

2.5. Climate change

Climate change impacts forests and forest ecosystems in multiple ways, such as changes to ecological conditions that impact how trees grow as well as through changes in human activities in response to the changing climate. The strong and direct impacts on forests are brought about by temperature, precipitation and carbon dioxide concentration changes associated with climate change. There are also anticipated effects related to the modification in the frequency and intensity of wildfires, insect and disease outbreaks as well as extreme weather events. Climate change could increase timber production in some regions through accelerated growth because of a warmer climate, forest area expansion toward the north and south poles, longer growing seasons and higher carbon dioxide concentrations (Kirilenko, 2007). However, it is uncertain that an increase in tree growth rates would offset the increased mortality due to the other climate change-induced impacts on ecosystems.

The development of a sustainable and circular bioeconomy can significantly help in reducing climate change impacts on forests and forest ecosystems as climate change and the use of raw materials are closely related and influence each other. Climate change can impact the availability of materials and system productivity while the accelerated extraction of materials contributes to increased GHG emissions and a worsening of climate change. Climate change also directly impacts ecosystem productivity and the availability of biomaterials. The increased risks of wildfire, drought, pest outbreaks, floods and other catastrophes require adaptation strategies and significant management actions to protect forests, the forest-product industry and associated workers to ensure the sustainability and the continued availability of all forest ecosystem products and services. The development of a sustainable and circular bioeconomy can significantly help in addressing climate change impacts on forests and forest ecosystems as climate change and the use of raw materials are closely related and influence each other. Canada's National Adaptation Strategy is an example of planning for climate change resilience at a national scale and includes addressing aspects such as nature and biodiversity as well as the related infrastructure, economic impacts, communities, and workers (Government of Canada, 2023). Also, climate change adaptation strategies and responses may lead to greater demand for materials due to, for example, a greater need to rebuild, repair and react to more frequent natural disasters (GACERE, 2021). A more circular economy aids in reducing the impacts of climate change by changing how materials enter and exit the economy.

One strategy for addressing climate change and contributing to a transition to a sustainable and circular bioeconomy is the development of carbon farming. Carbon farming rewards land managers for adopting improved land management practices that respect ecological principles and biodiversity that result in increased carbon sequestration in living biomass, dead organic matter and soils through enhanced carbon capture and/or reduced emissions (EC, 2021). This strategy is not the only one, where land managers can be rewarded for the stored carbon, this also applies to other forests, with the net carbon sequestration.

The financial benefits of carbon farming can be supported by public or private sources and existing carbon farming initiatives have enabled land managers to verify and sell carbon credits within regional, national and international carbon markets. The additional income from these sales contributes to the sustainability of forest land uses and supports investment in management to maintain, enhance and/or restore ecosystem functions. Effective carbon farming practices include afforestation and reforestation, agroforestry and perennial cropping systems, conservation tillage and soil protections as well as ecosystem restoration (EC, 2021). The development of carbon farming does not negate the need to also address the use of fossil-fuels and the resulting emissions that contribute to climate change.

Methods of industrial carbon capture, use and storage can contribute to achieving climate goals and be a replacement for fossil-carbon feedstocks for industrial production (EC, 2021a). Both carbon farming and industrial solutions are necessary to remove sufficient carbon dioxide from the atmosphere to avoid the worst consequences of climate change and both are necessary to achieve the EU's 2050 climate neutrality objective. Carbon farming works together with other Green Deal initiatives, such as the Forest Strategy, the Biodiversity Strategy and the Long-Term Vision for Rural Area as a win-win solution that generates new income possibilities for land managers along with environmental and social benefits. (EC, 2021a).

Circular material use emphasizes the retention of products, materials and resources in the economy for as long as possible and contributes to regenerating natural systems by reducing extraction pressures. A circular economy requires transforming linear economic models by expanding opportunities for materials and products to be kept at their highest possible value and to be retained within an economy through actions to reuse, repair, remanufacture, repurpose or recycle them (GACERE, 2021). Energy efficiency improvements and expanded use of renewable energy can address an estimated 55 percent of global GHG emissions, therefore, moving toward a sustainable and circular bioeconomy is essential to achieving the remaining 45 percent and reach net-zero energy emissions by 2050 (MacArthur 2021). Such transition can provide multiple benefits for sustainability, including climate change mitigation and reductions in GHG emissions, however, it requires innovation throughout economies and production systems for energy, water, construction, consumer goods and agriculture.

2.6. Pollution and waste

Global pollution is everywhere and includes negative impacts on land, water, and air. Pollution and waste are increasing problems and include impacts from chemicals, microplastics, air emissions, discharges to water, soil contamination, and damage to human health, ecosystems, and biodiversity. Global pollution is an increasing problem as volumes of waste rise and become unmanageable, and as dangerous and toxic forms of waste create complex challenges for short and long-term management and mitigation.

Material use is a proxy for environmental impacts that occur across the product life cycle from extraction, transformation, and consumption to disposal. When material use rises, environmental impacts, including pollution and waste, also increase. These impacts are realized in environmental, social and economic measures. The growing use of materials results in climate change, acidic and eutrophic soils and water resources, loss of biodiversity, and soil erosion. These trends impact human systems, health, and quality of life and lead to economic consequences with depletion of resources, supply chain disruptions, and shortages (UNEP, 2016).

Approximately 50 percent of global GHG emissions is due to the extraction and processing of the world's material resources which, at the same time, impacts biodiversity loss and leads to higher rates of pollution (GACERE, 2021). The environmental impacts of materials vary across material groups and life cycle stages. Metal extraction and processing have large toxicity and air pollution consequences; fossil fuel use emissions contribute to climate change and air pollution; biomass production (for food and feed) is linked to land use and water pollution; while non-metallic minerals have diverse impacts across land, water, air, ecosystems and biodiversity (OECD, 2019). The extraction, processing and use of seven key metals (iron, aluminium, copper, zinc, lead, nickel and manganese) have significant impacts on acidification, climate change, cumulative energy demand, eutrophication, human toxicity, land use, photochemical oxidation as well as aquatic and terrestrial ecotoxicity (OECD, 2019). These metals are essential to the continued growth of the global economy, including technology innovations, meaning their impacts will need to be managed and mitigated as demand rises. The total environmental impact of these metals' use is projected to more than double and, in some cases, even quadruple by 2060 (OECD, 2019).

Modern bioenergy devices, including boilers and stoves, can replace old appliances for cooking and heating, a step that can significantly improve air quality and human health. Such change-outs are especially effective and most beneficial when they replace open fires or old boilers and stoves that lack modern designs and technologies for greater fuel combustion efficiency and lower emissions. A study by the Bioenergy and Sustainable Technologies (BEST) research centre showed that particulate matter emissions from small wood-fired heating appliances in Austria can be reduced by almost 90 percent, while at the same time, the area heated with wood increases significantly (BEST, 2019). The effect can be achieved through high-efficiency devices and low-emission technologies.

Within the built environment and the use of construction materials there are varying pollution impacts. Although concrete has a smaller impact than metals on a per-kilogram basis, the volume of concrete is much larger than other materials and results in significant environmental consequences, particularly for climate change. The combined global pollution impacts of the seven key metals and concrete represent almost 25 percent of all GHG emissions and some 16 percent of cumulative energy demand (OECD, 2019). Reducing the expected impacts of the above requires consideration of alternative materials and greater use of biobased materials, including forest biomass, as substitutes whenever feasible. For example, innovative wood products, including mass timber, can contribute to a reduced reliance on concrete while renewable biomass energy can also reduce the emissions associated with heavy manufacturing.

A transition to a sustainable and circular bioeconomy requires a consideration of current pollution impacts and waste generation to design for improvement in material use, biobased alternatives and reduced emissions.

This transition requires an increase in the use of biodegradable, non-dangerous materials and the enhancement of design strategies to reduce waste. Biobased materials, including forest biomass, contribute to circularity by being renewable and having end-of-life alternatives that avoid waste generation and the impacts of disposal. Depending on the specific product or use, biobased materials can be allowed to biodegrade at the end of life or may be recovered for repair, reuse, recycled or utilized in the production of renewable biomass energy. Many biobased materials are naturally non-dangerous (non-toxic) and do not contribute to toxic forms of persistent pollution. Natural biobased materials are not subject to costly or complicated requirements for handling or disposal that can be necessary to address risks of contamination associated with other materials. Exceptions to this are biobased products that have been used with chemical treatments, adhesives or other additives beyond their natural biobased elements.

A significant goal of a sustainable and circular bioeconomy is the enhancement of material recovery and reuse. This can be done through greater emphasis on innovative design. Product design can directly address opportunities for disassembly and repurposing of a variety of wood products and other biobased materials. Wood construction products, as well as furniture and finished goods, can be designed for efficient recovery and reuse. Design can also reduce impacts associated with production systems, manufacturing and transportation by addressing efficiencies in material use to avoid byproduct and waste generation. Design can also address shipping demands and transport efficiency by increasing flat pack (ready-to-assemble) approaches while minimizing packaging materials and making them recoverable. These design innovations are essential conditions for a transition to a sustainable and circular bioeconomy and require cross-sectoral collaboration to identify improvement opportunities and appropriate solutions.

Another way to reduce pollution and waste is to recover usable materials from existing waste streams. This reduces the need to extract new materials while addressing capacity limits and other limitations of natural systems while avoiding the negative impacts on the environment associated with waste disposal. Recycling of materials from waste streams is an important innovation and can be expanded to enhance direct material reuse which requires less energy and GHG emissions than recycling processes that include remanufacturing of materials. For example, building deconstruction that allows the direct reuse of dimension lumber is an important innovation to support a transition to a sustainable and circular bioeconomy. The continued high rate of paper and packaging recovery from waste streams is also essential and can be enhanced through further system improvements and technologies.

Current linear economy models generate large volumes of waste from households and businesses, requiring an urgent shift in production and consumption patterns. However, a transition to a sustainable and circular bioeconomy requires conditions that support economic viability. The economic success of a transition also includes consideration of the environmental and energy footprints of pollution and waste management. Addressing these impacts remains necessary to ensure the sustainability of the economic system in the long term. A circular bioeconomy needs to be able to compete economically with the existing linear and fossil-dependent economy it is replacing. Improving the economic competitiveness of circular practices and the use of biobased materials requires gains in efficiency through productivity, material handling and resource use (Hertwich, 2020). Innovative policy frameworks, public-private partnerships, investment and research can also improve economic viability (Braatz, 2003; EC, 2018). In this context, incentives for a circular bioeconomy and disincentives for a linear fossil-dependent economy are important considerations within government actions.

2.7. Phasing out of plastics

Plastics are useful, versatile materials but the way they are used is wasteful. Plastics derived from fossil fuels are widely used and their use has increased steadily since the mid-1900s. This widespread use of plastics had, by the end of the 1990s, resulted in overwhelming pollution to the point of being detrimental to ecosystems, livelihoods and the economies depending on this material. Attempts to recycle plastics and remove them from the waste stream have had limited effect on the problem. At first, large volumes of plastic waste were collected and exported from high-income countries to be recycled in more remote places around the globe, including coastal areas with vulnerable economies that were dependent on industries such as tourism and fisheries. Gradually these plastics reached the oceans and, by the 2000s, this evolved into a global-scale problem. By 2015, global plastics production was 407 million tonnes, making plastics more widespread than the production of paper, fish, or aluminium (OECD, 2019). The economic cost of plastic pollution includes diminished fisheries, reduced tourism and direct clean-up costs which likely exceed USD 13 billion annually (UNEP, 2014). Plastic pollution is observable in all the world's oceans and an additional 5 to 13 million tonnes are introduced annually (OECD, 2019).

In recent years, many international initiatives have been undertaken to address the devastating impacts of plastic pollution. However, to address this global challenge a holistic approach is needed that combines the minimizing of the production and the consumption of new plastics, the development of safe and circular alternative options as well as the elimination of existing plastic pollution from the environment. The sustained focus on plastics has laid the foundation for a global plastics governance instrument. In 2022, the United Nations Environment Assembly approved a resolution to develop an international legally binding instrument on plastic pollution. The resolution underlines the importance of promoting sustainable plastic product and material designs so that they can be reused, remanufactured or recycled and, therefore, retained in an economy for as long as possible. This includes the resources these products are made of as well as minimizing the generation of waste, which can significantly contribute to sustainable production and consumption of plastics (IUCN, 2022).

In its blueprint for zero plastic waste, IUCN (2023) provides recommendations to implement circular economic models through approaches integrating drafting and improving legislation. This legislation is related to recyclability, waste management, domestic recovery facilities, product composition design, biodegradability and prevention of import/export of specific wastes that will support the prevention of plastic pollution. The aim of this innovative legislation and related policies is to keep plastic in the system and reduce reliance on linear models where plastic is directly disposed of in landfills and the environment.

Forest biomass and cellulose-based materials, in particular the different qualities and residues of pulp and paper, come into play as part of the solution to plastic pollution. Biomass provides an alternative and biodegradable resource in many current applications where plastics play a predominant role, including packaging, various single-use applications, textiles, and innovative materials used in the pharmaceutical, automotive and space industries. The growth of such biobased-product use in the United States has resulted in displacing approximately 9.4 million barrels of oil annually and potentially reduced GHG emissions by 12.7 million metric tons of CO_2e per year (USDA, 2018).

2.8. Consolidative Factors

As the interest in forest-based materials grows, there are several opportunities for the forest sector to benefit, including from additional investment, research prioritization and workforce growth.

2.8.1. Investment

With the opportunity to utilize forest-based materials to support a shift toward a sustainable and circular bioeconomy there are growing and diverse investment opportunities. In this regard, a wide variety of investment mechanisms are available for business development in the forest sector. Organizations with an interest in sourcing forest-based materials are investing in forest land management and supporting the stewardship, maintenance, and restoration of forest ecosystems by local communities. Investments in the forest sector include all aspects of providing sustainable forest-based materials, including tree seedling nursery and reforestation investments, land management, monitoring, inventory, harvesting and regeneration methods. The UNEP estimates that investment in forestry totalling more than USD 8 trillion is needed by 2050 to effectively address climate, biodiversity and land restoration needs (UNEP, 2021).

Such work is already underway as the FAO Forest and Landscape Restoration Mechanism (FLRM), for example, operates globally to address degraded landscapes by identifying and implementing practices that restore a balance of the ecological, social and economic benefits of forests and trees within a broader pattern of land uses. However, the success and impact of this work rely on sufficient investment, including innovation in local finance and business planning. Scaling up the development of sustainable forest-based value chains provides major climate and development benefits: increased productivity, increased carbon stocks (in forest assets, in wood products and through substitution of non-renewable materials and energy) as well as improved resilience against climate change effects. These investments contribute to reducing poverty through increased employment and incomes while also closing the gap between anticipated supply and demand because of population and economic growth.

Investors in a transition to a sustainable and circular bioeconomy include traditional financial institutions, philanthropic organizations, local interest groups, new investors with a focus on environmentally sustainable business models, social impact funds, business accelerators and incubation organizations. A growing number of financial interests and investors seek sustainable investments as a strategic objective. In 2021, USD 182 billion in green, social and sustainability bonds were issued globally, more than triple the amount issued in 2020 (The World Bank, 2022). These investor interests could be realized in the forest sector.

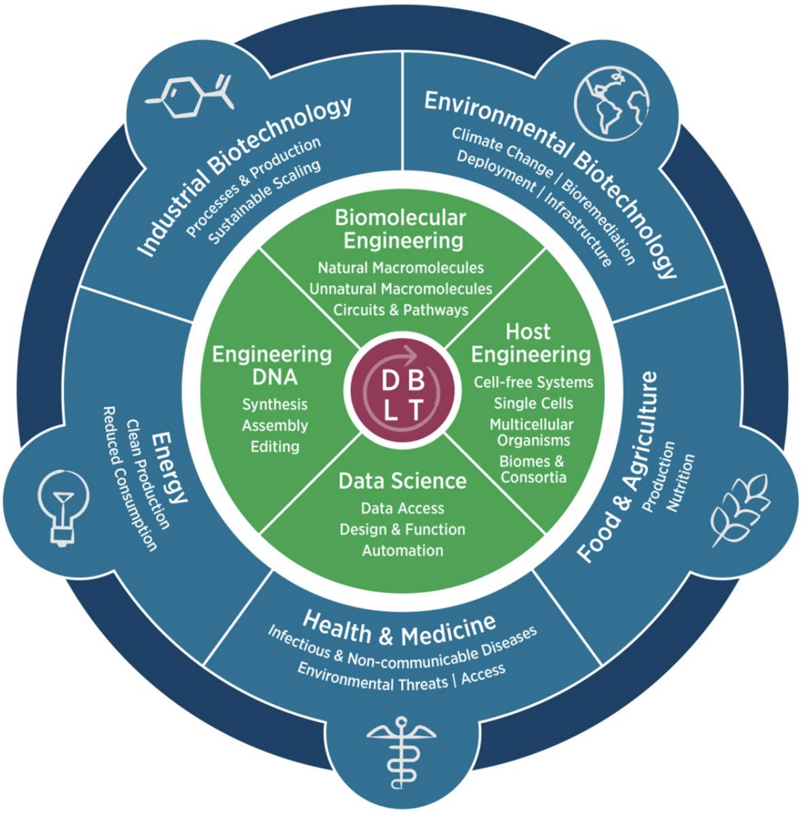
Investment efforts in advancing a sustainable and circular bioeconomy are particularly important because of the system change that is needed. Although it is common to imagine that barriers to a circular economy may be mainly related to technology, research has found that cultural barriers, including a lack of consumer awareness coupled with hesitant company cultures, are considered the main barriers to a transition towards a circular economy by businesses and policymakers (Kirchherr *et al.,* 2018). Market barriers are also a recognized issue that reflects a lack of sufficient government and policy actions in an appropriate mix to accelerate a transition (Ladu, 2020). Significant efforts will be needed to raise a transition to a sustainable and circular bioeconomy to a high priority for consumers, businesses and policymakers, and this will require investment in all domains.

2.8.2. Research prioritization

Core principles of a circular economy include: 1) designing to reduce or eliminate waste and pollution by creating new and optimizing old products for cycles of disassembly and use, and 2) making the most of both consumable and durable components of a product through processes like composting and anaerobic digestion, repairing, repurposing or upgrading the materials and products for a different use (UNECE/FAO, 2022). Pursuit of these principles requires investment in research, technology and innovation to support design and process improvements.

A bioeconomy is an established concept and there has been ongoing research investment in many related areas. For example, although other fields of scientific research have historically received more investment than biotechnology, the COVID-19 pandemic and the ability of the scientific community to develop tests and vaccines in record time brought the societal benefits of investments in biological sciences to the forefront. Overall research investments in a bioeconomy operate strategically across many national and global interests, including defence, energy, health, agriculture and aeronautics. In 2019, the Engineering Biology Research Consortium (EBRC) released a research strategy outlining technical themes and impact sectors that included calls for investment in industrial technology, health, medicine, food, agriculture, environmental biotechnology and energy for the bioeconomy. The potential expanded and innovative use of sustainable and circular forest-based materials fits within many of these themes and impact sectors (Figure 6). Central to the roadmap for a sustainable and circular bioeconomy research is the iterative Design-Build-Test-Learn (DBTL) cycle for bridging classical engineering disciplines with biological components and addressing their complex association with dynamic living environments (EBRC, 2019).

Figure 6 Research Roadmap for the Next-Generation Bioeconomy



Source: https://roadmap.ebrc.org/2019-roadmap/

2.8.3. Employment

Employment and job creation in the forest sector contribute to the implementation of the 2030 Agenda for Sustainable Development and support the achievement of several SDGs. Forest-related jobs are of relevance to SDG 1 'No poverty', SDG 3 'Good health and well-being', SDG 5 'Gender equality', SDG 8 'Decent work and economic growth', SDG 13 'Climate change' and SDG 15 'Life on Land'.

To stay competitive, the forest sector continuously adapts to regional, national and global developments, such as those resulting from trade, business and technology development. It also continuously responds to the structural changes facing resource-based sectors, such as the globalization of commodity markets, changing population trends and an ageing workforce. Technological developments and evolving priorities in forest management (from timber production to ecosystem management) are also changing the nature of forest work and any transition towards a sustainable, and circular bioeconomy will need to be included in these priorities. This shift requires new skills in the forest sector workforce.

The services linked with a transition to a sustainable and circular bioeconomy will create changes that can save labour and energy, address some of the workforce challenges and overcome capacity limitations in some sectors, including forestry. A transition toward a sustainable and circular bioeconomy can create new workforce growth, career pathways and labour innovations. These innovations and expanded job opportunities include environmental and social cross-cutting issues, such as ecosystem management in forestry, climate change mitigation and adaptation, a green economy, gender equity, effectively engaging and supporting an ageing workforce as well as adaptation of skills to technological developments (UNECE/FAO, 2019).

Chapter 3 Conditions for a successful transition

Forest ecosystems are an essential element of a transition towards a sustainable and circular bioeconomy. This transition requires that the interactions between forest ecosystems be fully considered, including the environmental, economic and social aspects.

A sustainable and circular bioeconomy can support diverse and abundant forests and the ecosystem services they provide. This can be realized through the effective use and development of SFM and forest operations as well as regenerative forestry activities, landscape restoration and adaptive forestry. For the environmental conditions of a sustainable and circular bioeconomy to be resilient, ecosystems' boundaries and balance among forest ecosystem services need to be respected. Through a considered approach it will be possible to ensure the sustainable provisioning of ecosystem services for the needs of a sustainable and circular bioeconomy in the long term.

In addition to environmental conditions, a transition to a sustainable and circular bioeconomy needs to consider economics and the sustainable production and consumption of wood products. Through the design and production of wood products that are renewable and biodegradable there can be greater intentional circularity in material use. Wood residues from production processes can also be effectively recovered and utilized as a raw material for other products, including those produced outside the forest sector. A sustainable and circular bioeconomy relies upon the increased recovery of these materials and enhancements in the number of cycles that products and materials remain in use. These improvements can be achieved through innovation in recycling, technology development, changes to logistics and other system changes.

While a transition to a sustainable and circular bioeconomy is a global goal, local production and consumption are key economic conditions to consider in achieving it. Whenever possible, local economies, including green job opportunities, should be developed to support the use of natural resources in ways that reduce the impacts of production and consumption, shorten supply chains and improve outcomes for people and the planet.

Consumers also have an important role to play in creating the general conditions that are needed for a transition to a sustainable and circular bioeconomy through behaviour that supports the products, materials and benefits associated with this economic model. On the production side, many industries' workforces will need to adapt skill sets, training and abilities to align with sustainability and circularity.

A review of literature reveals that the fields of research required to support a transition to a sustainable and circular bioeconomy includes a wide range of subjects. The diversity of research areas is reflective of the diversity of forests as natural systems as well as the diversity of the ecosystem services and products they provide. Research has included analyses of models to minimize GHG emissions through cascading use of wood resources, surveys of public perceptions of biomass energy, testing of many forms of biomass for a wide range of potential products and materials as well as the role of a circular economy in enforcing sustainable forest development (Lazaridou, 2021). Research has found that improvement is realized through energy and material efficiencies that improve competitive advantage and include better use of organic waste, sustainable material flows, utilization of residues, creation of added value and local jobs, more professional and qualified employment, and poverty alleviation (Lazaridou, 2021).

There are concerns about maintaining a balance between the demands for biomass and the sustainable provisioning of forest ecosystem services. Within the scope of any economic transition, there must be protection of biodiversity, land and soil resources, food systems and other essential services. Many policies and practices have already been established and are being expanded within the forest sector to maintain a balance between the demands of a growing bioeconomy with the capacity to provide a full spectrum of forest ecosystem services. They include, for example, international collaboration in monitoring and reporting as well as market-based mechanisms, such as certification and eco-labels, that help maintain a balance. These existing strategies are important conditions that support a successful transition to a sustainable and circular bioeconomy.

3.1. Environmental Conditions

Environmental considerations for a transition to a sustainable and circular bioeconomy include respecting the natural cycle of forests, the ecological limitations of forest ecosystems and the sustainable provisioning of raw materials. Forests are natural systems that, on a small scale, contribute to local environments and landscapes but at the global scale play a role in issues such as climate change.

Biomass resources for the needs of a sustainable and circular bioeconomy can be derived from four main sources: 1) agricultural land; ii) forests; iii) urban and roadside vegetation; as well as iv) food, and municipal waste (Hamelin, 2019). Evaluations of available biomass in Europe have estimated that enough material is available from these supply sources to provide the equivalent of 2015's primary energy consumption of Italy and Belgium combined (Hamelin, 2019). Additional research concluded that by 2050 bioenergy could provide 25 percent of the total energy consumption in EU-28 (based on 2016 levels) and about 40 percent of the bioenergy could be from forest biomass (Faaij, 2018). The trend toward a sustainable and circular bioeconomy is driven by the need to address resource constraints related to climate, water, energy and land as well as by advances in microbiology and shifts in consumer preferences (von Braun, 2018).

Wood is a key renewable resource used for creating biodegradable and recyclable materials. Production residues for primary wood manufacturing processes can be reused in cascading systems that result in minimum waste. All forest-based products are biobased and are therefore both renewable and can naturally decompose if properly designed. However, a circular bioeconomy cannot be sustainable without the sustainable provision of forest biomass, based on SFM, regenerative forestry activities, landscape restoration, and adaptive forestry.

3.1.1. Respecting the natural carbon cycle of forest

The natural carbon cycle is an important concept to consider as it includes emission sources as well as storage capacity. There are four main carbon storage categories within the natural carbon cycle: (1) sedimentary rocks; (2) the oceans; (3) plants and animals (the biosphere); and (4) the atmosphere.

Forests are important for the natural carbon cycle in the services they provide by removing carbon dioxide from the atmosphere, storing it, continuing that storage in long-lived wood products and providing biobased alternatives to fossil-based materials that result in reduced emissions. Carbon moves through its natural cycle via a variety of processes, including chemical weathering, photosynthesis and the cycles of plant and animal life. As such, climate change and other environmental conditions influence the natural carbon cycle. For example, chemical weathering results in carbon being absorbed in the world's oceans and depends on rainfall, which in turn depends on temperature and is thereby affected by atmospheric conditions. As carbon dioxide levels in the atmosphere increase, there is a corresponding increase in chemical weathering. Photosynthesis also increases as plants use the carbon dioxide in the atmosphere in their growth. Increases in chemical weathering and the growth of plant and animal life can result in more carbon dioxide being absorbed from the atmosphere and transferred into ocean storage, biotic carbon sinks and terrestrial soils. However, carbon emissions also occur through organic decay and decomposition as well through events like wildfires. These emission sources may also increase as climate conditions change. Therefore, feedback loops and trade-offs must be considered within the conditions for a transition to a sustainable and circular bioeconomy. Forests' growth cycles and the natural carbon cycle are both important for a bioeconomy and are reflected in the many components of global sustainable development strategies. These strategies, including the 2030 Agenda for Sustainable Development and the SDGs, provide holistic frameworks to enable effective and sustainable interactions between local communities and economies within the context of these natural cycles.

Effectively addressing the complexity of natural cycles and diverse forest ecosystems in a transition to a sustainable and circular bioeconomy requires integrating the SDGs with additional policy frameworks to prioritize supportive activities and consideration of research findings related to barriers. A transition towards a sustainable and circular bioeconomy at the global level is an effective way to achieve an economic model which can increase environmental, economic and social sustainability at all levels and reduce dependence on non-renewable fossil resources.

Research has categorized drivers and barriers to a transition to a circular economy, including the distinct areas of change to be addressed: environmental, economic, social, political and institutional, technological and informational, supply chain and, finally, organizational factors (Tura *et al.,* 2019; Gomez, 2021). The environmental barriers include consideration of resource constraints and prevention of negative environmental impacts.

3.1.2. Supporting forest ecosystems' services

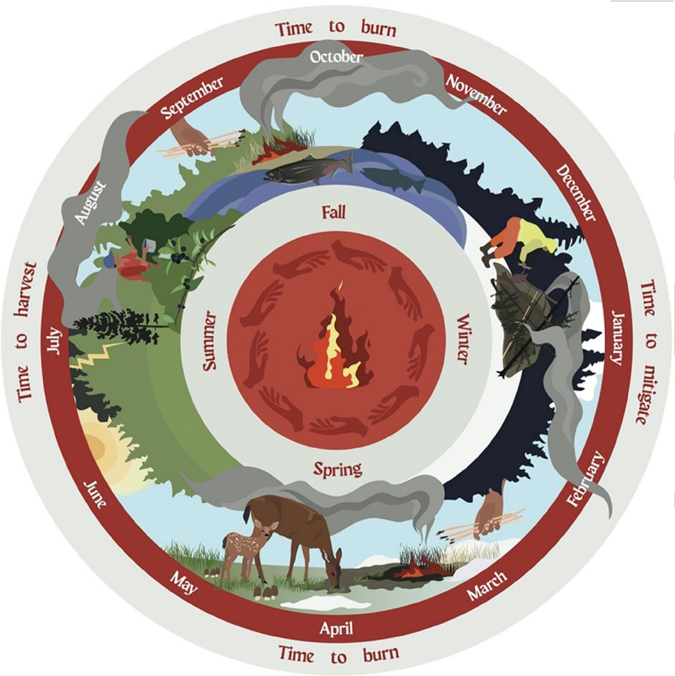
The world contains an extraordinary diversity of forests existing in a variety of different geographical, landscape and climate conditions and circumstances. The natural global forest diversity impacts life on the entire planet and the capacity of ecosystems to respond to climate change, the other consequences of human activity and a transition to a sustainable and circular bioeconomy. The forest conditions that are present around the world, such as tree species composition, age distribution and other features are a result of the histories of land use changes and environmental impacts over many generations.

Many ecosystems have been significantly altered, degraded and otherwise impacted in ways that affect their natural cycles and resiliency to the growing threat of climate change. The ecological stability of natural systems is threatened by the impacts of climate change, including changes in available moisture, temperature extremes and other types of variability that are outside of historic averages. These changing conditions are different from what local species may be best suited to for their survival.

Forests have developed under the influence of historic climatic and ecological patterns, including intentional cultural interactions, that have impacted the current composition of forest ecosystems and their ecological response systems. The suppression of traditional caregiving practices for forests, such as the reduction in natural fire, has protected forests and their carbon stocks but at the same time contributed to current concerns about forest health, including rising wildfire risks in some regions. As such, the restoration of Indigenous style burning can be a part of strategies to support forest health (Kimmerer, 2001). The use of fire as a resource management and cultural tool by Indigenous Nations has been researched in Australia, Canada and the United States (Mawson, 2021; Hoffman, 2022; Kimmerer, 2001). There is also research in Northern Australia on a behaviour described as *fire-spreading* that occurs when raptors fly to an active fire (i.e. a cooking fire or a wildfire), pick up smouldering sticks with their talons or beaks, transport them up to a kilometrere away, drop them in brush or grass, and thereby start a new fire ignition point (Bonta, 2017).

Figure 7 illustrates the seasonality of Indigenous fire stewardship and other effective practices to balance fire with various land uses, depicting inter-generational continuity and community-based relationships with fire, embedded in knowledge that has been passed down for millennia.

Figure 7 A seasonal calendar illustrating aspects of Indigenous fire stewardship



Source: Hoffman, 2022.

There is a widespread need to care for the land through restoration, protection and stewardship activities at the local, regional and global scale. Human communities have an essential role in supporting forest ecosystem services through the thoughtful application of SFM, regenerative forest activities, landscape restoration and adaptive management. Some of the skillsets needed for a transition to a sustainable and circular bioeconomy include Indigenous Traditional Ecological Knowledge (ITEK) and the strengthening of relationships between ITEK and other research methods as well as scientific practices within academic institutions and between communities of practice.

3.1.3. Sustainable forest management

In 2007, the United Nations General Assembly recognized SFM as a dynamic and evolving concept that aims to maintain and enhance the economic, social and environmental values of all types of forests for the benefit of present and future generations. In doing so, it considered the following seven thematic elements as a reference framework: (1) extent of forest resources; (2) forest biodiversity; (3) forest health and vitality; (4) productive functions of forest resources; (5) protective functions of forest resources; (6) socio-economic functions of forests; and (7) legal, policy and institutional framework.

Sustainable forest management is essential to the sustainable provisioning of forest-based materials and all ecosystem services. The aim of SFM is to ensure that forests supply goods and services to meet both present-day and future needs while simultaneously contributing to the sustainable development of communities (FAO, 2017).

Sustainable forest management encompasses administrative, legal, technical, economic, social and environmental aspects of the conservation and use of forests (FAO, 2017). It also implies a degree of intentional and reciprocal human interaction with ecosystems. These actions may be undertaken with the intention of safeguarding and maintaining forest ecosystems and their functions, to address specific social or economic values as well as to produce goods and services. In addition to forest products, including both wood and non-wood materials, sustainably managed forests provide many ecosystem services. Important ecosystem services provided by forests and supported through SFM include carbon sequestration, biodiversity conservation as well as the protection of water, air and land resources.

However, not all forests are being managed sustainably around the world and there are barriers to further and more beneficial applications of SFM. Effective application of SFM may require changes in forest legislation, regulation and incentives as well as additional funding, research and human resources for the preparation, implementation and monitoring of forest conditions, management plans and other SFM activities. To ensure the social dimensions of SFM are addressed, it is also necessary to establish and maintain mechanisms for the participation and involvement of all stakeholders in forest governance, planning and development. Therefore, in SFM practice, forest management plans must ensure not only the sustained production of wood and non-wood products but also the sustainable management of all ecosystem services while maintaining social and environmental values (FAO, 2017). For that reason, SFM is an essential precondition for a transition to a sustainable and circular bioeconomy and is related to additional goals and strategies for restoration and adaptive management.

Healthy ecosystems enhance people's quality of life counteract climate change and reverse the loss of biodiversity. Restoration actions aim to recover ecological functionality, enhance human well-being and provide significant benefits to address the impacts of climate change, including carbon sequestration and a reduction of GHG emissions (Garrett *et al.,* 2022).

Led by the United Nations Environment Programme (UNEP) and FAO, the UN Decade on Ecosystem Restoration (UN Decade) runs from 2021 to 2030 and is a global movement to provide momentum to restoration efforts restoration and put the world on track for a sustainable future (UNEP, 2021). Actions include building global political momentum for restoration as well as local initiatives. The United Nations General Assembly proclaimed the UN Decade following a proposal for action by over 70 countries.

The UN Decade calls for the protection and revival of ecosystems all around the world so they can provide benefits for both people and nature. These global efforts and commitments aim to halt the degradation of ecosystems and restore them in alignment with identified global goals, including the SDGs.

Forests are one of the eight types of ecosystems addressed in the UN Decade, as forest and land degradation affect almost 2 billion hectares (ha) globally and threaten the livelihoods, well-being, food, water and energy security of nearly 3.2 billion people (Garrett *et al.,* 2022).

Many large restoration initiatives have been launched in conjunction with the UN Decade that have provided cost-effective approaches to mitigate climate change, improve ecosystem resiliency and support a transition to a sustainable and circular bioeconomy through the responsible provisioning of forest resources. Forest and landscape restoration is also one of the key solutions of the agriculture, forestry and other land-use (AFOLU) sector, considered in the United Nations Framework Convention on Climate Change (UNFCCC) and confirmed in the Glasgow Declaration on Forest and Land during the twenty-sixth UNFCCC Conference of the Parties (COP26).

National Policy Guiding Principles for Forest Landscape Restoration is a tool for national forest authorities engaged in FLR, which aims to support them in identifying and adapting their national FLR-related policies, strategies and laws according to available best practice and evidence. The NPGP are composed of thematic and cross-cutting principles, which contain basic ideas or rules explaining how FLR should work. Each principle is introduced by a rationale, followed by a set of proposed criteria (i.e., the requirement that must be met to consider that the principle is applied), and a short description of the expected benefits.

3.1.4. Adaptive forest management

With SFM as the foundation, the merging of restoration goals at the landscape scale with local application of Adaptive Forest Management (AFM) provides a holistic approach to caring for forest ecosystems in ways that are sustainable, restorative and adaptable to changing conditions. This integrated and adaptive approach to forest management recognizes the inherent capacity of forest ecosystems now and in the future to self-organize and adapt to changing environmental conditions. This future-oriented thinking and resiliency-focused mindset is an advancement from outdated management models that attempted to restore ecosystems to a previous historical state (Bolte, 2023; Spathelf, 2018). Given the significant and growing influence of climate change on ecosystems and their ecological responses, it is increasingly ineffective to limit management actions and desired outcomes by referencing past conditions. The past may no longer be a sufficient source of information to predict ecosystem responses to expected future conditions. Therefore, the use of innovative ecosystem modelling, new research findings and traditional ecological knowledge is needed to address the complexity of change conditions. Research has also considered the strategy of non-management (i.e. no action or no intentional human interaction) as an approach for forest adaptation to climate change. Results indicate that productive forests have properties that require continuous or even increased efforts by forest managers to be maintained (Jandl *et al.,* 2019). Forests, especially productive forests, have been influenced by many different land use and economic development decisions. Adaptive forest management may provide a response to that as it includes intentional and thoughtful human interactions that contribute to the health and resiliency of diverse forest ecosystems.

3.1.5. Respecting ecosystem boundaries

Respecting ecosystem boundaries as one of the planetary boundaries relates to all actions avoiding transgressing a critical threshold for increasing risks to people and the ecosystems health and regeneration. Natural forest ecosystems are diverse and resilient, having evolved across highly varied climate conditions around the globe. They can regenerate following devastating natural disturbances such as wildfires, hurricanes, floods and volcanoes eruptions. However, forest ecosystems can be disrupted in ways that create imbalances in the provision of ecosystem services and forests' natural recovery mechanisms may be too slow or insufficient to avoid devastating consequences for people and the environment. To avoid these outcomes, it is necessary to respect the forest ecosystems' boundaries, restore greater ecosystem resiliency through global restoration initiatives and balance the provisioning of services in ways that are sustainable and contribute to a thriving circular bioeconomy. Accomplishing this requires a deep understanding of natural ecosystem boundaries, ecosystem services and their sustainable provisioning.

Monitoring of the world's forests coverage and health, as well as related research, are essential conditions for a transition to a sustainable and circular bioeconomy. One such area of related research is biomimicry, a complementary concept for approaching an understanding of nature and forests as well as for visualizing and supporting a transition to a sustainable and circular bioeconomy. Biomimicry is the concept of imitating natural biological designs and processes in engineering or invention to create new products, services and sustainable models. This concept has been to some extent applied in forestry, through close to nature forest management.

Through this approach, nature is a model for meeting the challenges of sustainable development.[3] The application of biomimicry to a transition to a sustainable and circular bioeconomy can enhance the alignment of production and consumption models with natural systems and ecological functions. For example, nothing in nature is wasted as the by-products of one process or species' activities become the inputs for another. This way the production and consumption cycles are connected and complete. This approach can provide inspiration for circularity models.

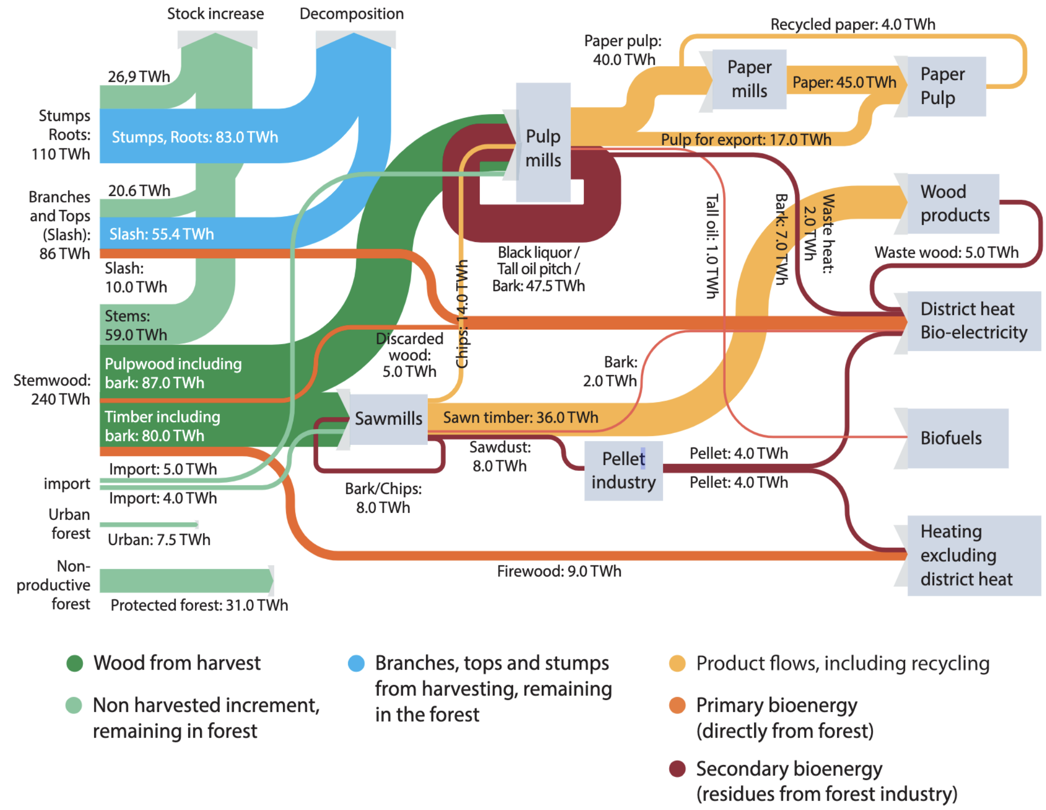
3.2. Economic conditions

A transition to a sustainable and circular bioeconomy depends on the sustainable production and consumption of forest-based materials. In 2018, the global production of and trade in major wood products surged to their highest level since FAO began recording forest statistics in 1947. The value of international trade in wood products was 11 percent higher than in 2017 with the fastest growth occurring in North America, Europe, and the Asian-Pacific region (FAO, 2019). The consumption of post-consumer recovered wood is also essential to a transition to a sustainable and circular bioeconomy and from 1980 to 2020, it is estimated that the production of recovered paper increased by 352 percent, including a 59 percent rise since 2000 (FAO, 2021).

Forest-based materials can be used for a wide variety of products and innovation continues to develop new and expanded uses. New and growing opportunities include the development of biobased fuels, chemicals, renewable energy, and other industrial products to help address climate change and reduce dependence on fossil-based and non-renewable raw materials. These innovations create economic and job creation opportunities. Forest biomass is available from a variety of resources and contributes to a wide range of uses, including bioenergy applications (Figure 8).

[3] Center for studies & expertise in biomimicry (CEEBIOS) https://ceebios.com/biomimetisme/

Figure 8 Biomass and energy flows from Swedish forests



Source: IRENA, 2019 (Also cited in Cowie *et al.,* 2021) https://www.researchgate.net/figure/Biomass-and-energy-flows-from-Swedish-forest-Source-IRENA-2019_fig1_351438063

The principles of a circular economy are well aligned with common production practices in the forest sector and the manufacturing of forest-based products. Many tenets of a circular economy are already applied in the forest sector. A circular bioeconomy study was undertaken involving a Finnish forest products company and its production of biofuels, biocomposites and biochemicals. The study focused on the renewable diesel produced from the side streams of the pulp production process and the company's use of materials that would have otherwise been waste products. Compared to fossil fuels, renewable diesel produced fewer GHG emissions and thus reduced the use and reliance on non-renewable resources (Tura *et al.,* 2019). The development of renewable diesel from their side streams was driven by environmental and economic factors, however, the initial investment costs and risks to financial return presented barriers (Tura *et al.,* 2019).

In addition to biofuels and biochemical opportunities, solid wood products used for construction purposes can also contribute to a lower carbon footprint for buildings and reduce reliance on fossil-based materials. Wood, cellulose, as well as its derivatives (such as lignin), are a viable substitute for non-renewable materials. Furthermore, reusing and repurposing materials through lumber salvage and paper recycling are common practices in the sector and, as such, forests and forest-based products can play a key role in a sustainable and circular bioeconomy by providing a renewable source of raw materials. A more coordinated approach aiming to tap into the full potential of the forest sector, including the more widespread use of manufacturing and post-consumer residues, can turn this sector into one of the key pillars of a sustainable and circular bioeconomy.

Along with the forest management adaptations to climate change, there is also a need for industry adaptations that consider new types of wood and products to support a transition to a sustainable and circular bioeconomy. Although climate change brings negative forest-health impacts and challenges, adaptive forest management coupled with forest industry innovations can help address these. For example, the forest industry is engaged in innovations and research to more fully utilize tree species that have been underutilized in the past and may be appropriate for use in new products and materials. The industry is also adapting to improve the utilization of species that are disproportionately impacted by declining health conditions due to climate change, increased insect and disease outbreaks, wildfires and other changing ecological factors. Examples of this include the use of dead and dying trees in the development of mass timber technologies and cross-laminated timber products. By providing utilization opportunities for these materials the industry can help offset the costs of forestry operations related to SFM and climate adaptation actions. A reduction in costs can result in more areas being appropriately treated and effectively cared for so that the benefits of ecosystem maintenance and restoration occur at a greater scale to provide environmental, social and economic benefits to communities.

3.2.1. Design and production of renewable and biodegradable wood products

To achieve a robust transition to a sustainable and circular bioeconomy it is necessary to intentionally design and produce wood products that provide the benefits of being renewable, biodegradable, and recoverable at the end of life. Besides the fact that wood products must come from sustainable sourcing of forest-based resources to ensure renewability, products must also be designed with end-of-life alternatives in mind, including recycling, reuse or recovery for energy production.

Research into the opportunities to utilize forest-based materials to support a transition to a sustainable and circular bioeconomy has included reviews of a wide range of possibilities. It has included examinations of sugars production, wood residues utilization as raw material for fertilizers and as a soil liming agent, utilization of by-products for the creation of insulation panels, use of fly ash from forest biomass combustion as a potential additive replacing calcite in cement-based mortars and the development of wood–plastic composite materials as well as other alternative uses (Lazaridou, 2021).

Biobased plastics provide benefits to the environment because they are made from renewable materials and reduce the dependence on fossil fuels which contribute to climate change as well as many forms of waste and pollution that impact the environment and communities. Nevertheless, caution must be considered with the use of biobased plastics as a substitute for fossil-based plastics to ensure that they are designed for circularity and reduced ecosystem impacts. Like fossil-based plastics, biobased plastics can be manufactured in chemical compositions that cause them not to biodegrade. Biodegradability depends on the chemical composition of the plastic. Bioplastics can be biobased and biodegradable or biobased but not biodegradable. Government policies and strategies for plastic reduction should include set targets for biodegradability, recyclability and compostability to help ensure that bioplastics are designed to achieve these outcomes and exempted from bans or penalties for single-use and highly polluting plastics. The EU has established a policy framework (within the European Green Deal, the Circular Economy Action Plan, and the Plastics Strategy) to address the identification of biobased plastics and ensure consumer understanding of those materials that are biodegradable and compostable (EC, 2022). A transition to a sustainable and circular bioeconomy must consider the preferred use of biobased materials as well as the end-of-life alternatives to include designing products for material reuse and recovery or non-toxic disposal options, such as composting or biodegrading.

The IPCC and other research have consistently reported that the most important climate change mitigation measures are those that result in the transformation of energy systems, including the decarbonization of industrial energy use and transportation systems. These system changes are underway but need to be accelerated. The development of Sustainable Aviation Fuels (SAF) utilizing biomass feedstocks is an example of a strategic transition toward sustainability. Biomass utilized for SAF production can be provided through forest management that generates sustainable forest health thinnings, forest operation residuals (e.g. slash and bark) and wildland fire mitigation material (US DOE, 2022). Biobased materials have a key role to play in achieving climate change goals and reducing emissions. The substitution of biomaterials contributes to the decarbonization of high-emitting sectors such as energy production, transportation, and industrial manufacturing.

Bioenergy plays an important role as an immediate and direct alternative to fossil fuels that can be implemented now and rapidly scaled in support of an energy-system transition. Bioenergy implementation offers opportunities for forest-product operations to be partners in and sources of resources for meeting local energy needs, including services for rural populations and Indigenous communities. There are differing viewpoints on the role of forest-derived bioenergy resources and the quantification of the climate impact of their use as an alternative to fossil energy. The natural variation in forest ecosystems and SFM approaches contribute to the differences in quantified impacts and varying assessment methods also contribute to misconceptions of forest bioenergy. For example, analysis that isolates small areas of forest or focuses on emissions associated with combustion does not address the interactions of ecosystems at larger scales and the full natural carbon cycle. To effectively inform energy policy and related bioenergy investments, it is necessary to adopt a systems approach for assessing forest bioenergy that includes: (1) consideration of the whole life cycle of bioenergy systems, including effects of forest management on landscape carbon balances; (2) identification of forest bioenergy strategies that can best support energy-system transformations that contribute to climate goals; and (3) incentives for those systems that enhance the mitigation value of the forest sector as a whole (Cowie *et al.,* 2021).

Technologies combining bioenergy plus BECCS provide additional potential benefits. The development of BECCS includes a combination of carbon capture and storage with the use of biomass as an energy source to provide the potential to produce negative emission technology (NET) (Fajardy, 2017).[4] Canada's "Mid-Century Long-Term Low-Greenhouse Gas Development Strategy" identified large-scale afforestation and BECCS as approaches to achieve negative emissions as well as areas for further research, including the increased use of wood products for carbon retention in buildings (Craik, 2022). The emissions-reduction potential of BECCS in the US has also been studied and estimated to represent a pathway to achieving as much as 33 percent of the goal of net-zero GHG emissions by 2050 (Energy Futures Initiative, 2022).

[4] For discussion of conditions for BECCS, see: The High Level Panel on BECCS Done Well, 2022. For a literature review addressing BECCS, see: Energy Futures Initiative. Surveying the BECCS Landscape. 2022.

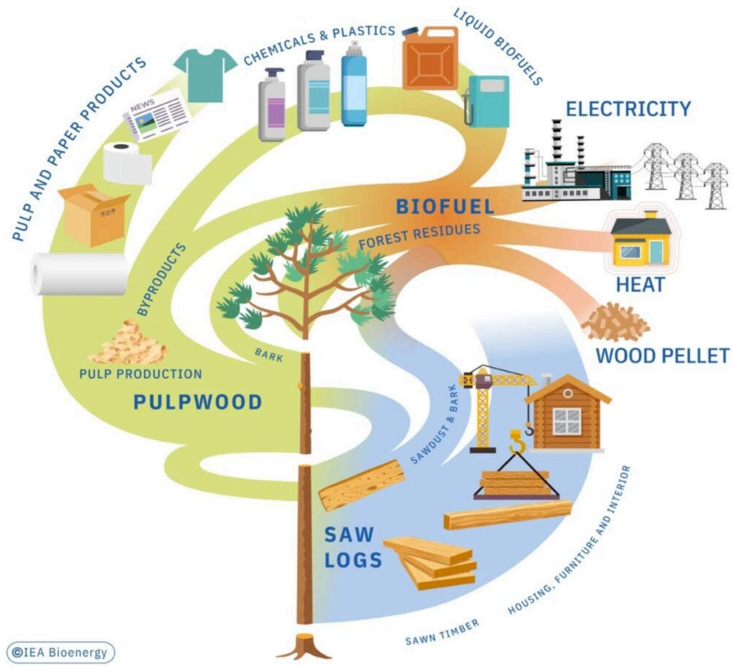
Industrial decarbonization includes the reduction of carbon emissions and implementing carbon capture for the production of cement, steel and other materials that contribute significantly to global emissions. Decarbonization of these production processes is essential to meeting climate change mitigation goals and forest products are a part of the solution. The world's cement industry is responsible for about 25 percent of all industrial CO_2 emissions, however, there are pathways to reduce these emissions by 75 percent by 2050 through a combination of energy-efficiency improvements, alternative fuels, material substitution and new technology (McKinsey, 2023). Similar strategies apply to the decarbonization of steel manufacturing and other industrial processes. The US Department of Energy's (DOE) Industrial Decarbonization Roadmap identifies four key technological approaches that could result in 100 percent of annual CO_2 emissions from American manufacturing being mitigated. These four strategies are energy efficiency; industrial electrification; substitution of low-carbon fuels, feedstocks and energy sources (LCFFES); and, finally, carbon capture, utilization and storage (CCUS) (US DOE, 2021).

The forest sector contributes to industrial decarbonization by providing low-carbon fuels, feedstocks and energy sources. Biomass energy and biofuels can provide electricity generation as well as renewable thermal heat required for many manufacturing processes. Carbon-storing products, such as biochar, can also be incorporated into industrial products like concrete, wall board, plastics and asphalt. Research demonstrates biochar's potential as an effective CO_2-storing material in cement-based applications, similar to its use as a soil amendment (Akinyemi, 2020). The environmental impacts of cement and steel can also be reduced by utilizing wood-based alternatives in the built environment that lower the embodied carbon associated with construction material choices (ODF, 2022).

3.2.2. Recovery of wood residues as a primary source of raw material

The availability of wood residues is directly linked to the production volumes of the major products made from wood, including paper, construction materials and value-added goods. The efficient use of harvested wood and efficient recovery of wood residues can be achieved through a diversified forest products market that includes demand for pulpwood, saw logs and biofuels in a variety of consumer goods, energy systems and the built environment (Figure 9).

Figure 9 The efficient use of harvested wood for wood products, paper and energy



Source: https://www.tandfonline.com/doi/full/10.1080/02827581.2016.1240228?cookieSet=1# [5]

As recently as the 1940s, up to 45 percent of harvested roundwood (i.e. logs) could not be processed into lumber or other useable products due to limitations in technology and other factors (i.e. sawmill design, lack of composite product manufacturing technologies, limits in chip and by-product utilization) (Bowyer, 2012). Through product innovation in the subsequent decades, including the development of fibreboards and diverse laminated products, forest product companies were able to find uses for the by-products of lumber production, resulting in the possibility for greater utilization of the harvested wood (Bowyer, 2017). The energy embargo and oil supply disruptions in the 1970s pushed the industry further as by-products from forest-product manufacturing became an important source of renewable energy generation (heat and power). Rising fossil fuel prices and the drive for renewable sources of affordable energy led to the wider use of wood-based energy, both internal and external to forest-product manufacturing industries. Continued innovation in fibre recovery, energy efficiency and manufacturing technology resulted in a forest sector that, by 2005, had largely eliminated waste within its primary processing facilities (Howe, 2013). Similarly, progress within pulp and paper manufacturing has occurred through the development of pre- and post-consumer recycling capacity and end-of-life alternatives that include composting and bioenergy.

An additional area of innovation to support a transition to a sustainable and circular bioeconomy is the development of mechanisms to divert wood from waste streams through the improved utilization of urban and reclaimed wood from cities and communities. Urban wood includes logs from trees growing in urban areas and wood elements from construction and demolition (Lyon, 2014). Urban and

[5] *Source*: How can the ambitious goals for the EU's future bioeconomy be supported by sustainable and efficient wood sourcing practices?
Richard Sikkema http://orcid.org/0000-0003-0954-3469, Jean Francois Dallemand, Cristina T. Matos, Marijn van der Velde & Jesus San-Miguel-Ayanz
https://doi.org/10.1080/02827581.2016.1240228

reclaimed wood companies are firms that produce value-added products with logs from trees growing in urban areas and wood components generated through construction and demolition (Pitti *et al.,* 2020), Materials that would otherwise be waste. With the growing interest in wood and other biomass, such entrepreneurial industries and innovative business models enable the improved recovery of these materials and greater opportunities to avoid landfill disposal. Furthermore, this drives economic growth and local production as well as opportunities for raw material management to salvage these materials and increase their use for higher-value products (Pitti *et al.,* 2020). Urban and reclaimed wood products contribute provide consumers with unique and sustainable products. The sustainability of these products is associated with the recovery of otherwise biobased waste material and also contributes to their increased role in a sustainable and circular bioeconomy.

These changes in the forest sector provide an example of the types of technology innovations, market diversifications and systems changes that are needed to transition toward a sustainable and circular bioeconomy. The forest sector has made significant progress in this direction and a goal of a more complete transition is achievable Improvements in construction/deconstruction debris recovery and recycling of solid wood products are currently areas of focus for the forest sector. new raw materials in the form of additional wood harvests are added to the system but at a lower rate than would have occurred in the absence of the improvements in utilization technology that have occurred. These changes have directly contributed to a global wood consumption rate that has increased but at a lower rate than that of population growth.

Although wood use in construction offers substantial sustainability and circularity benefits, additional innovation is still needed. Currently, waste from building deconstruction or demolition is not being recovered effectively. Designing for building adaptability or disassembly and effective material recovery needs to be accomplished to improve the circularity of wood in the construction sector. The data suggests that there is considerable room for improvement in wood recovery and recycling at the end of life for buildings.

Several other factors also contribute to challenges with a transition to a sustainable and circular bioeconomy, including the complexity of managing biomass feedstocks. Efficient feedstock handling systems and continued innovations in this area of operations are essential. Biomass feedstocks are considered complex due to their variability in physical attributes as well as their chemical composition and mechanical performance.

3.2.3. Production and consumption from local resources whenever possible

Business models designed in line with a sustainable and circular bioeconomy principles can be classified as those that 1) mainly contribute to the reuse and extension of products and materials, or 2) produce new goods using recovered materials. Forests and wood products can contribute to both types of business models. Wood products can be readily repurposed and reused while new products can be made from recovered wood materials. Examples of these business models are already evident in the urban and reclaimed wood industries. The reclaimed wood industry extends product life through remanufacturing while urban logs are used by the urban wood industry to produce lumber, flooring and other value-added products (Pitti *et al.,* 2020).

3.2.4. Socioeconomic aspects

The social aspects of a transition to a sustainable and circular bioeconomy align with the objectives of the SDGs which means meeting the needs of the present without compromising the ability of future generations to meet their own needs.

In 2020, the European Forest Institute (EFI) published a 10-point "Action Plan for a Circular Bioeconomy of Wellbeing" that provides a roadmap to ensure that nature is positioned at the core of a transition to a sustainable and circular bioeconomy (Palahí *et al.,* 2020). The ten elements of the plan include focusing on sustainable wellbeing; investing in nature and biodiversity; generating an equitable distribution of prosperity; rethinking land, food and health systems in holistic ways; transforming industrial sectors; reimagining the ecology of cities; creating an enabling regulatory framework; delivering innovation to investment and political agendas; enabling access to finance and enhanced risk-taking capacity; and, finally, intensified and broadened research and education activities (Palahí *et al.,* 2020).

Within the social aspects of a sustainable and circular bioeconomy, the drivers for a transition include increasing the awareness of sustainability requirements among producers and consumers within the economy and supply chains. This can contribute to increasing external and market-driven demand for sustainability and related investment in sustainable development projects, including strategies for transforming industrial sectors (Tura *et al.,* 2019). Research has provided a framework for categorizing drivers and barriers to a transition to a circular economy, including seven distinct areas: environmental, economic, social, political and institutional, technological and informational, supply chain and, finally, organizational factors (Tura *et al.,* 2019). These barrier categories identified by the study include 1) region-specific and local cultures' limitations that impede the implementation of new solutions (e.g. in some cultures, excessive consumption is associated with social success); 2) the conservativeness in business practices (e.g. in the waste management industry); and 3) lacking or uncertain customer needs related to sustainability and circularity (Tura *et al.,* 2019).

One of the pivotal factors that can bring solutions to the identified barriers is the need for producer and consumer behaviour changes to support a transition to a sustainable and circular bioeconomy. Research has identified that businesses and policymakers view low consumer interest and awareness, along with hesitant company cultures, as the main barriers to implementing a circular economy (Kirchherr *et al.,* 2018). Sustainable production and consumption patterns can be promoted at different levels in policymaking, business-to-business marketing and business-to-consumer engagement. Additionally, the benefits of a sustainable and circular bioeconomy may be demonstrated and subsequently effectively communicated to change existing patterns and behaviour.

Besides the limitations related to cultural aspects and the production and consumption patterns, the expanded and accelerating demand for materials, including biobased materials, can lead to local conflicts over land use and the allocation of resources. Global materials use is projected to double by 2060 with the strongest growth expected in emerging and developing economies, including China, India, Indonesia and most countries in sub-Saharan Africa and Asia (OECD, 2019). Conflicts associated with material extraction are readily apparent in energy and mining activities globally and, in some instances, have led to wars and impacts beyond the local communities. Conflicts also occur between competing agricultural land uses and with urban and suburban development activities. Large investments in material extraction and production can create economic opportunities in a region but also incur consequences and trade-offs to consider in terms of environmental impacts and the elimination of alternatives due to incompatible uses.

3.2.5. Job creation

The World Economic Forum (WEF) estimates that the sustainable management of forests could create USD 230 billion in business opportunities and 16 million jobs globally by 2030. Furthermore, a transition to a circular economy across multiple sectors, including food, land and ocean use; infrastructure and the built environment; and extractives and energy, could lead to USD 2.3 trillion in business opportunities and 30 million jobs over the same timeframe. Looking at the most comprehensive level of transition, the Future of Nature and Business report by the WEF estimates that robust sustainability and circularity throughout the global economy could generate up to USD 10.1 trillion in annual business value and create 395 million jobs by 2030 (World Economic Forum, 2020).

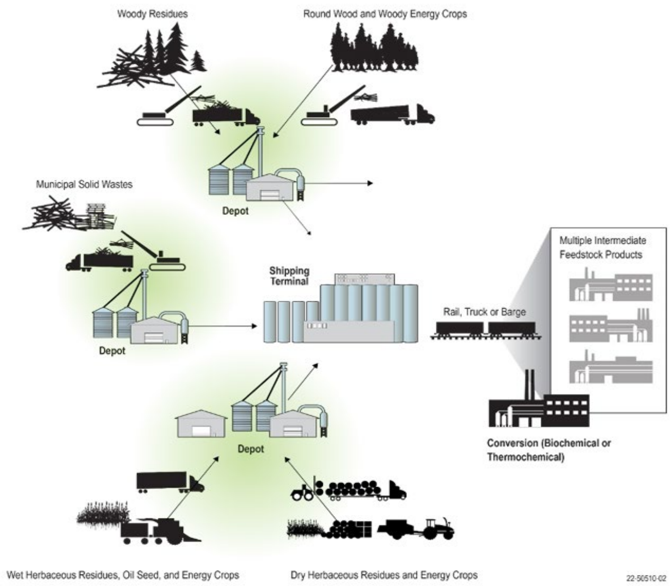
In the United States, a 2016 estimate contained in a Joint Federal Agency Report, published by the Biomass R&D Board, had a much more conservative estimate of the impact of the domestic bioeconomy, indicating over a quarter million jobs and an economic contribution of approximately USD 50 billion by 2030. This estimate, however, excluded from its considerations established forest and agricultural sector jobs (including those related to production, processing, and distribution of food, feed and fibre), as well as the pharmaceutical sector. With these caveats, the report addressed the potential growth of a domestic bioeconomy, estimating that by 2030, with efficient use of the roughly one-billion-tonne annual biomass supply identified in earlier studies, total direct revenue could reach approximately USD 250 billion annually, with a total economic impact of USD 660 billion each year including indirect economic outputs. The report further indicated that the cumulative job benefit could amount to over a million new positions that cannot be outsourced from the United States (Rogers *et al.* 2017).

3.3. Governance and policy factors

In the context of increasing demand for raw materials and forest-based products, there is a need for greater coordination between the productive cycle of forests and the technical cycle of forest-based industries. This coordination exists to some degree in current markets and supply chains but will need to be strengthened to maximize circularity along the various value chains. Supply chain optimization is needed to increase the availability of biomass and improve forest ecosystem health while also reducing the cost and improving the quality of wood-based feedstocks from land management, construction and demolition waste (US DOE, 2022). Additional research and development investment is needed to support the improvement of d harvesting systems, including in the areas of transportation, storage and preprocessing, to increase efficiencies while decreasing costs and carbon intensity (US DOE, 2022).

There are opportunities to improve existing supply chains and organizational factors in ways that are immediately available and easily aligned with current operations. These strategies include scaling up current models that work, replication of operational systems and enhanced investment, including greater workforce engagement. There are also possibilities for the adoption of more substantial changes to enhance a transition to a sustainable and circular bioeconomy. This includes innovative, disruptive and system-wide changes that can contribute to more significant changes in supply chains and result in meaningful improvement of outcomes for forest ecosystem health and restoration. A disruptive strategy is more likely to produce an advanced supply system and newly formed supply chains that result in redistributing biomass resource supply risks (US DOE, 2022). This type of innovation contributes to greater economic and operational resiliency which is important for a sustainable circular bioeconomy. An example of an improved supply system strategy is the depot system for biomass feedstocks proposed by the Idaho National Laboratory in the United States (Figure 10). The system moves supply risk to an intermediate facility (the depot) that processes biomass to meet market demands (specifications) and reduces both transportation costs and inefficiencies. Similar systems are already widely used in agriculture and food production to create centralized collection points for large volumes of raw materials allowing efficient transport to diverse domestic and global markets. Expanded use of these supply chain strategies, including the associated producer collaboration, could improve environmental outcomes through reduced transportation-related emissions and enhance the economic competitiveness of forest-based enterprises. These approaches have begun to be more widely developed in wood-pellet production and contribute to the potential for renewable bioenergy to provide an alternative to fossil fuels and aid in the decarbonization of industrial value chains.

Figure 10 Example of advanced logistics depot system.



Source: Figure by Idaho National Laboratory, published in US DOE report

3.3.1. Cooperation along and across value chains

A transition to a sustainable and circular bioeconomy and greater sustainability requires cooperation among all the actors along and across value chains. Innovation and collaboration between public and private sector organizations are important to enhancing material recovery, reuse, avoided waste and greater circularity. Partnerships and cooperation are essential to improving efficiencies in raw material sourcing and recovery. By way of example, the emergence of urban and reclaimed wood production facilities has seen these firms utilize an average of four partners for their raw materials sourcing, including diverse public and private sector collaborators (Pitti *et al.,* 2019).

Improvements in value chain management, including incremental changes as well as more substantial disruptive innovations, are generated through public and private sector investments in research and development. Further breakthroughs will be realized as specific research findings are applied to business and supply chain operations. For example, there is ongoing development of electric logging equipment to reduce the reliance on fossil fuels and avoid emissions associated with wood harvesting. Similar innovative research is occurring in the agriculture and transportation sectors. Given the cross-sectoral opportunities for a transition to a sustainable and circular bioeconomy, there are possibilities to identify changes and innovations from other industries that apply to the forest sector. These innovations may come from aspects of supply chain logistics employed in agriculture, traditional energy generation or other sectors that are adaptable to forest-product needs.

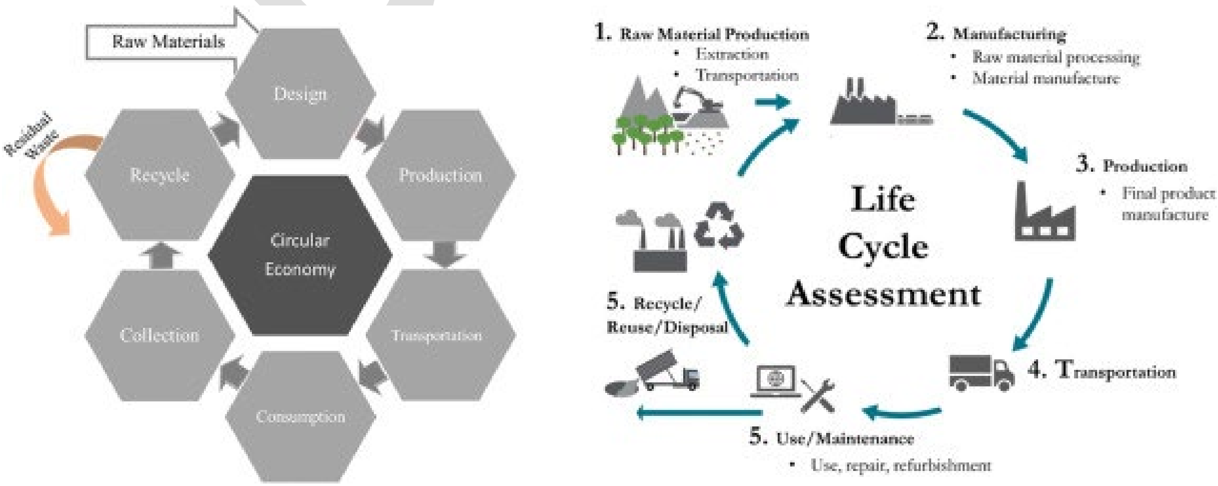
A transition to a sustainable and circular bioeconomy includes opportunities for business innovation, including new models, products and services. In a review of Finnish perspectives on the bioeconomy, the emergence of new forest-based businesses was considered essential to a successful transition. Existing forest sector firms viewed themselves as forerunners of a circular bioeconomy valuing the importance of Finnish forests for carbon sequestration and sustainable raw materials (Näyhä, 2019). Similarly, a review of the Canadian perspective showed that existing efforts by forest industries to increase circularity in manufacturing and reduce resource consumption were acknowledged, however, implementation of other strategies, such as reuse, recycling and energy recovery, were less prevalent (Gagnon, 2022).

A transition to a sustainable and circular bioeconomy can be supported through incremental improvements, such as utilizing recovered lumber in manufacturing and avoiding the mixing of paper recycling streams. However, several more substantial cultural, regulatory, technical and market-based barriers must also be addressed through a suite of cross-jurisdictional government interventions and clear policy direction at the national level (Gagnon, 2022).

3.3.2. The role of LCA

Life cycle assessment (LCA) is an important scientific tool for evaluating the sustainability of products and manufacturing processes that can contribute to greater circularity. An LCA is a detailed analysis that relies on the extensive use of data and quantifiable environmental impacts, including energy input and emissions to air and water, that are tracked through life-cycle inventories. It is an approach that considers multiple aspects of a product or manufacturing cycle and can parallel the considerations applicable to a circular bioeconomy (Figure 11).

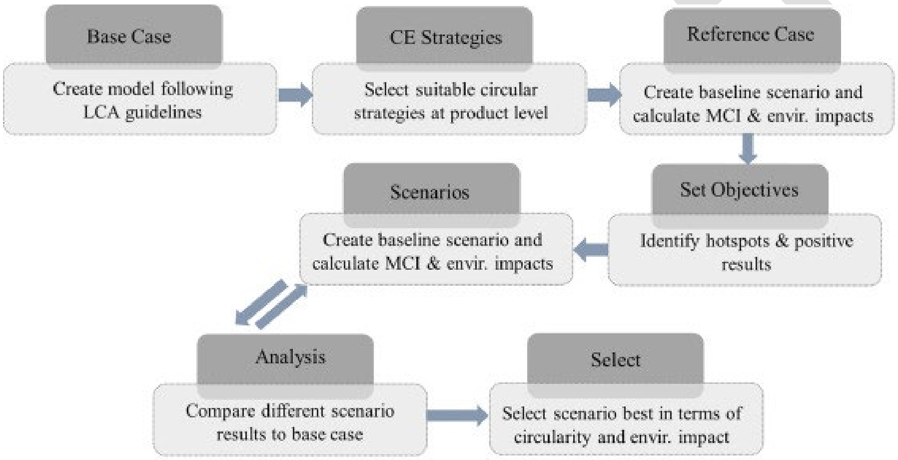
Figure 11 A Circular Economy and Life Cycle Assessment



Source:(Stefanakis and Nikolaou 2021.) (Chapter 9) (link to image)

An LCA can consider system alternatives that address reductions in resource use, emissions to air and water as well as in waste generation while increasing the range of renewable and recyclable material choices. It provides the most direct evaluation and quantifiable results for the first three considerations mentioned above. Additionally, it can complement the development of great circularity by evaluating alternatives and associated impacts as well as assisting in setting goals for improving outcomes in manufacturing and material use and recovery. Combining circular bioeconomy goals and strategies with LCA ensures the efficient mobilization of businesses to achieve proven benefits for people and the planet. There are seven distinct steps for integrating a circular economy and LCA (Figure 12) and providing an iterate process for optimization across alternatives (Stefanakis and Nikolaou 2021).

Figure 12 Integration of A Circular Economy and Life Cycle Analysis



Source: (Stefanakis and Nikolaou 2021.) (Chapter 9) (link to image)

Life cycle assessment studies of various materials have shown that because wood is renewable, biobased and grown in nature, it has lower overall environmental impacts than other industrial and consumer materials like steel, concrete or plastic (Lippke *et al.*, 2004). Additional LCA research specific to the improved sustainability of using reclaimed wood found that the recovery of wood products can reduce energy consumption used in the production of new wood products by 11 to 13 times and this contributes to reclaimed wood having much lower global warming potential (Bergman, 2010).

3.3.3. Regulations and institutional drivers

In 2015, the European Commission adopted the Circular Economy Action Plan and provided a list of measures to be taken to enhance a forest-based bioeconomy and forest-based industries. A transition to a sustainable and circular bioeconomy requires the development of an effective policy framework that necessarily includes support for many aspects, including investment in research, technologies and changes to production systems. There has already been a wide range of relevant policies implemented to address multiple aspects of the forest sector and its role in a sustainable and circular bioeconomy. Existing policies consider social, economic and environmental factors, including responsible and transparent supply chains, labour regulations and fair business practices. Alignment of these policies with a shared objective for a transition to a sustainable and circular bioeconomy is key to creating systemic change. Furthermore, the policy mix that best enables a transition to a circular bioeconomy is one that combines "climate mitigation policies" with "sustainable forest management policies", "R&D policies" and "awareness raising policies" (Ladu, 2020).

Policymakers are aware of the economic barriers and challenges that limit a transition to a sustainable and circular bioeconomy. The development of biobased industries can be slowed by the high costs of research and long development timelines for bringing new products to market with economic benefits (BIO, 2022). To support the development of a sustainable and circular bioeconomy, innovative policies have been developed that allow companies to monetize their research and development (R&D) efforts as well as a more traditional system of favourable tax treatment, credits, or exemptions (BIO, 2022). Policies can provide multiple benefits when they are also designed to support the decarbonization of manufacturing operations. Tax credit policy mechanisms and programming can support decarbonization by recognizing forest biomass as a renewable fuel. Sectors with lengthy commercialization timelines can have three distinct phases of development that relate to distinctive policy mechanisms. Aligning policies with specific sector needs can contribute to greater success with a transition to a sustainable and circular bioeconomy. Policies such as those shown in Table 2. Three Phases of Biobased Company Development and Associated Policy Support Mechanisms. have been implemented in 46 states and territories of the United States and, in 2018, the bioscience industry contributed USD 2.6 trillion to the national economy (BIO, 2022).

Table 2 Three Phases of Biobased Company Development and Associated Policy Support Mechanisms

Company Development Phase	Company Descriptive Features	Associated Policy Support Mechanisms
Early Stage	A company is beginning to verify viability with early testing. It has no products on the market, has less than 100 employees and is financed by a variety of private or venture fund sources.	Small business technology funds, investor tax credit, seed capital tax credit, incubator/accelerator funding
Mid State	Technical viability has been established, target product has been developed but significant investment is often needed for personnel, equipment and facilities (commonly less than 200 employees).	Net operating losses, R&D tax credits, investment tax incentives
Manufacturing	The company manufactures commercial quantities of an approved product, creates a sales force or licenses its product to another company. Traditional sources of financing may become viable.	Site and infrastructure grant funds, renewable energy tax credits, utility rebates, tax discounts, exemptions and refunds

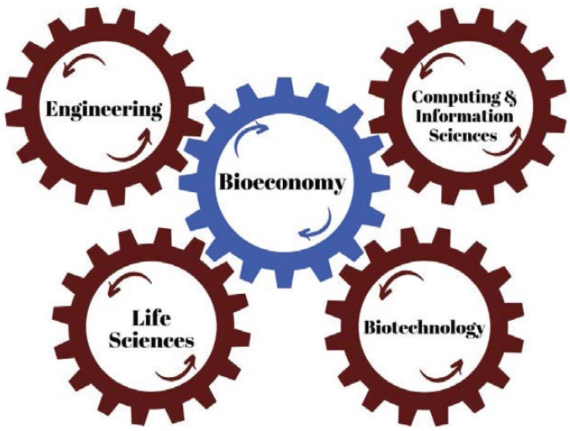
Source: (BIO, 2022)

The particularities such as the complex knowledge base, fragmented policy schemes and diverse innovation types, cause challenges for the design of business models for bioeconomy (Bröring, 2022). Research has defined three generic business model types specific to a bioeconomy, namely 1) new biobased products, 2) new biobased processes, and 3) integrated (biobased) services (Bröring, 2022). Progress with research to conceptualize business models that are directly applicable to a sustainable and circular bioeconomy contributes to defining a clearer research agenda for the sector and informs policy actions, investment choices and decision-maker priorities. The growth of the bioscience industry has been enabled by policies that build career pathways for workers, provide market and product development incentives, apply technology to improve manufacturing processes, invest in infrastructure and research, enable public-private partnerships, facilitate entrepreneurship and address supply chain risks (BIO, 2022).

Subsidies are a recognized strategy to create enabling business conditions in an economy and have long been used to influence material use and energy systems. Materials and energy production derived from fossil-fuel resources have benefited from a variety of subsidy and incentive approaches for many decades (Antimiani, 2023). The abrupt removal of subsidies from established and mature industries can raise concerns about harmful economic disruptions as well as negative impacts on both investors and communities that depend upon reliable, affordable energy and other abundant material supplies. Similarly, the creation of new subsidies or incentives for emerging sector innovations that may be viewed as high-risk or unproven may raise concerns about the appropriate use of government policy and public funds Given the need to transition from an existing linear economic consumption model to a sustainable and circular bioeconomy, it is likely that many systems, including subsidies, will need to be altered. It is also likely that multiple strategies will be needed to achieve the desired transition.

The simultaneous implementation of multiple policy instruments, such as those proposed under different EU climate strategies may provide an opportunity for an effective approach that includes the removal of subsidies to fossil fuels and the redirection of public revenues to foster the technological transition of the energy system for a sustainable and decarbonized EU economy (Alessandro, 2023). These considerations and potential policy innovations have gained urgency following the lessons learned from COVID-19 and the associated need for system recovery as well as the ongoing energy crisis. There is a dichotomy of policy and research viewpoints on whether the COVID pandemic has created an opportunity or a threat to the energy and other economic transitions that were underway prior to 2019 (Mišík, 2023). A similar dichotomy is also present in the discussion and perception of the EU's energy and climate policy in response to the Russian invasion and any temporary or longer-term changes related to energy security and decarbonization priorities. Continued analysis of the energy and climate policy dimensions of the EU’s post-pandemic recovery is needed to clarify the extent of the energy security crisis connected to the Russian invasion of Ukraine (Mišík, 2023).

Figure 13 Four Drivers of a Bioeconomy



Source: National Academies of Sciences, Engineering, and Medicine National Academies of Sciences, Engineering, and Medicine. 2020.

A bioeconomy is based on four drivers as shown in Figure 13engineering, life sciences, biotechnology, and computing and information sciences (National Academies of Sciences, Engineering, and Medicine, 2020). Besides these, a bioeconomy is supported by natural resources, scientific research and innovation. The development of a bioeconomy includes products of biological processes and biological feedstocks as well as the value chains that have formed to support the related research and production activities. Through these connections a bioeconomy creates opportunities for the convergence of many different scientific and engineering principles and domains within the life sciences, an interdisciplinary nexus that is key to a bioeconomy's success and growth (National Academies of Sciences, Engineering, and Medicine, 2020).

The forest sector can play an important role in a sustainable and circular bioeconomy as innovative and essential forests-based materials contribute directly in the fields of engineering, biotechnology and renewable energy as well as in other industrial products and applications. Forests also connect to the life sciences through the importance of the environment to mental and physical human health and vibrant communities. The continued development of computing and information sciences, including research findings, aid in the growing understanding of forests and identifying effective ways to support a transition to a sustainable and circular bioeconomy while continuing to support the full spectrum of forest ecosystem services.

Chapter 4 Conclusions

The forest sector, which is situated in both the biological and technical cycles of a circular economy, has a major role to play in a transition to a sustainable and circular bioeconomy. Therefore, this study has examined the context for understanding and effectively managing the increasing interest in forest-based materials ensuing from such a transition.

Forest resources in a circular economy as a sustainable alternative to the linear use of fossil-based materials

Forest-based resources provide several sustainable alternatives to meet the growing demand for raw materials and energy, thus contributing to an effective reduction of the global reliance on fossil fuels, related CO_2 emissions and, in general, a more sustainable use of natural resources.

The fact that forest-based resources provide sustainable alternatives to fossil-based materials is related to the restoration cycle considered unique to biomass, namely, that opposite to fossils, biomass can regenerate, and where waste biomass contributes to the formation of new biomass through restorative material flows that return a resource to nature, for example, through composting or bioenergy. This can be thought of in mass-balance terms of CO_2 at the start and the end of the biomass lifecycle, which particularly holds true once emission-free energy is available. Cascading use in terms of down-cycling until the remaining fibres are burnt should then be avoided as far as technically feasible.

The theoretical concept of a circular economy, which is often compared to a perpetual motion machine, is not attainable in many circumstances. The objective is to reduce waste and limit the consumption of finite resources to achieve sustainability in the long term. More sustainable practices, which already represent an improvement that can be measured against existing economic models, do not aim to transform the entire global economy into a circular bioeconomy at all costs. Therefore, this study considers several challenges and opportunities for the forest sector related to the ongoing transition to a sustainable and circular bioeconomy.

Factors affecting the sustainable provision of forest biomass in a circular bioeconomy

As forest ecosystems are diverse and widely distributed around the world, they can make a widespread and substantial contribution to the sustainable production and consumption of forest-based materials. They are also highly valued by rural, suburban and urban communities for a variety of ecosystem services of significant importance to local economies and the quality of life. However, the growing demands on ecosystems to provide biomaterials must stay within the ecological boundaries of the sustainable provisioning of forest-based materials. An essential condition for a sustainable and circular bioeconomy is that all forest functions are ensured.

Aside from these growing demands, there are many other threats that create pressure on ecosystems. Forest ecosystems are directly affected by deforestation, especially in the Global South because of expanding agriculture and other land-use changes while wildfires and pests impact sustainability and system resilience. Many of these threats are worsened by the effects of climate change. The latter, as well as other global challenges such as pollution, waste and the phasing out of plastics, create not only threats but also opportunities for the forest sector.

Conditions for a successful transition to a sustainable and circular bioeconomy

A sustainable and circular bioeconomy includes environmental, economic and social aspects that relate to forests and the forest sector. These aspects include supply chains and organizational factors, policy innovations and public and private institutional roles. The transition to a sustainable and circular bioeconomy can be facilitated by policies and regulations that are based on the capacities of public and the private sector, available (waste) resources and market conditions. Policies can support resource efficiency, waste minimization as well as better planning and decision-making to facilitate integration across sectors. A sustainable and circular bioeconomy will be the result of transformational processes across entire value chains and require new business models, public-private collaboration as well as the adoption of innovative technologies and tools.

Cooperation and collaboration at the global scale are essential elements for the successful transition to a sustainable and circular bioeconomy. They should, among other things, build on partnerships between the Global South and Global North as well as withing them. Essential natural resources are often available in the Global South that, in turn, may require support to promote innovations, technologies and investments to ensure the sustainable use of their resources. The Global North, on the other hand, contributes to the growing demand for products and biomaterials. Additionally, as future supply sources in the Global North may face challenges in meeting the needs of growing demand, biomaterial supply from the Global South will contribute to balancing global markets. Consequently, the alignment between supply and demand at a global scale is an important condition for an effective transition to a sustainable and circular bioeconomy.

The elements of cooperation and collaboration for a sustainable and circular bioeconomy include an enhanced understanding of industrial ecosystems and their connections with businesses and local communities. Forest value chains include a wide range of stakeholders and depend on available forest resources. Local communities, including Indigenous Peoples, are vital stewards and partners in a sustainable and circular bioeconomy. Their traditional knowledge and long history of sound practice as responsible landowners and forest managers contribute to positive economic transitions and outcomes.

The social impacts and potential results of a transition to a sustainable and circular bioeconomy will generate the need for new skill sets at all levels. This includes employee development via training and innovative educational curricula. Some of the new skillsets will need to take aboard ITEK as well as the relationships between ITEK and other research methods and scientific practices. Forests have a special place in a sustainable and circular bioeconomy because of their deep connections to Indigenous People's diverse and abundant ecosystem services, along with their capacity to regenerate and provide resilience and livelihoods in a changing climate and evolving world.

Opportunities and challenges of wood products for forest-based-industries resulting from a transition to a sustainable and circular bioeconomy

Among the various products provided by trees and forests, wood can play an important role in the transition to a sustainable and circular bioeconomy because it is a renewable material with many natural and beneficial attributes. It is used in various industries, such as wood construction, chemicals and textiles, where cross-laminated timber and cellulose-based textile fibres are seeing the most significant growth.

As industry boundaries blur, forest-based industries adopt new value chains and more and more sectors increasingly rely on wood as their primary raw material. Many wood-based products are under development. Some promising early-stage products include wood foam, glycols, bioplastics, lignin-based adhesives and wood-based composites, all of which are expected to enter the market within the next two decades.

To fully realize this potential, it is important to ensure that the conditions for material recovery, renewability, biodegradability and sustainability are enhanced for wood-based materials. Maintaining and further developing long-lived value chains is also essential for waste reduction.

The existing dominant economic model is based on linear uses of raw materials and contributes to escalating environmental, health and social risks. A sustainable and circular bioeconomy allows communities and societies to maintain sufficient economic performance and limit damage to human health while, at the same time, reducing the environmental footprint on ecosystems and the planet overall. Application of the concepts of biomimicry and industrial ecosystems can enhance the alignment with natural systems and economic efficiency.

The full potential of forests in a sustainable and circular bioeconomy can be realized through a never-wavering focus on the principles of SFM supported by incentives, investments and regulations. These need to be coupled with innovation and modernization across industry as well as a trained and skilful workforce allowing for the optimized cascading use of wood at every manufacturing step. This needs to be done in partnership with an expanded commitment to material reuse, including the greater recovery of post-consumer wood. A transition to a sustainable and circular bioeconomy should focus on holistic approaches that extend beyond specific products. Natural cycles of forest health and growth, the carbon cycle and the expansion of landscape-restoration activities can all be supported in a sustainable and circular bioeconomy to contribute to reversing trends of biodiversity loss and ensuring that all forest functions thrive.

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