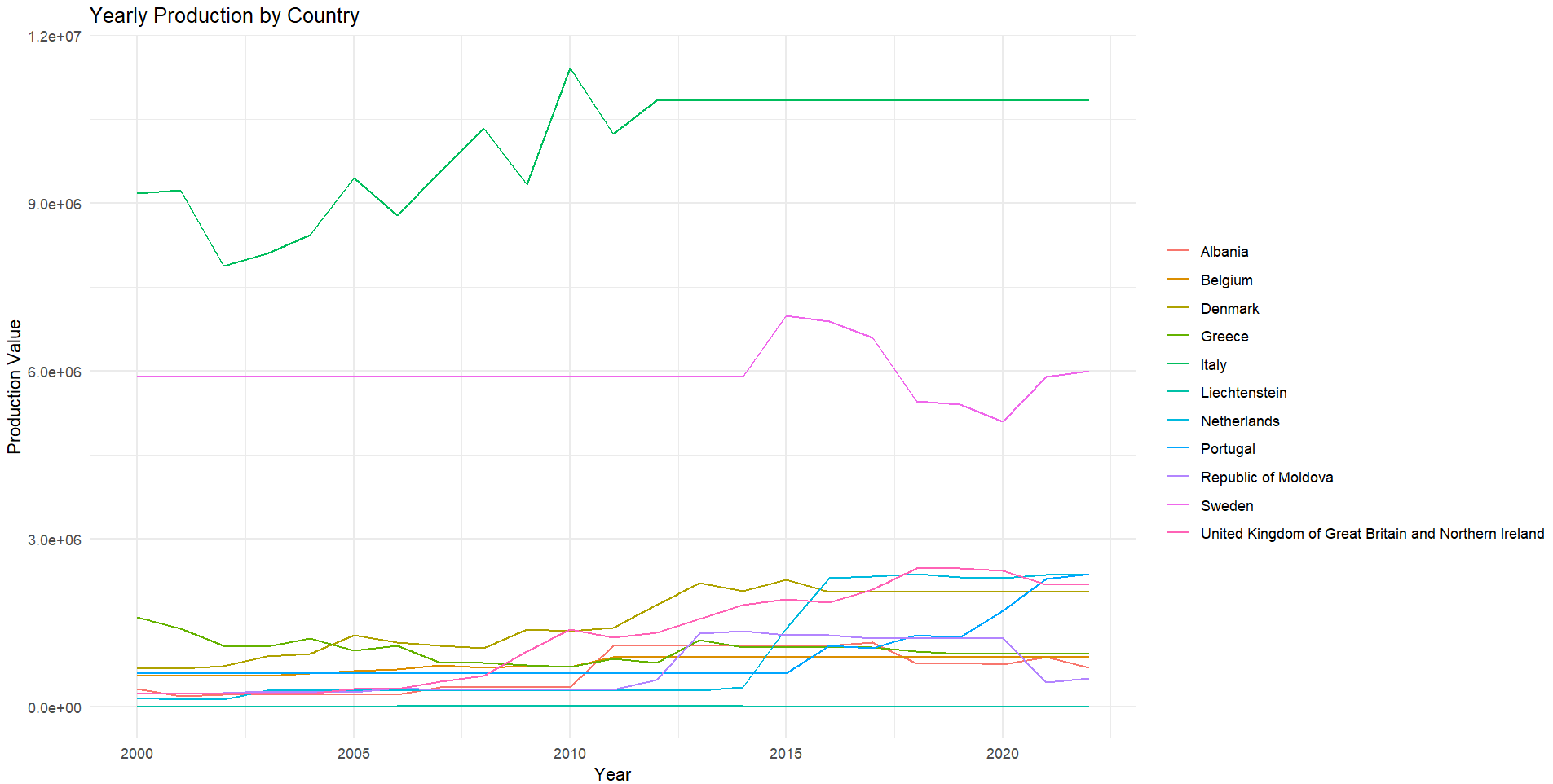
**Supplementary materials**



**Figure 1.** Annual wood production of various countries from 2000 to 2022 (million cubic meters)

**Table 1.** Summary of the studies analyzed in the literature review

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Author Name** | **Country** | **Scale** | **Reference year(s)** | **Data source** | **Data parameter** | **Approach** | **Limitation** |
| Buongiorno (2021) | World | Global | 2018-2070 | Official statistical data | Production, trade, forest area, and forest stock | GFPMX | Fuelwood are underestimated |
| Bais *et al*., (2015) | World | Global | 1990-2010 | Official statistical data | Import, export of wood industry, pulp industry, paper industry, other industry and final consumption along with recycled wastes. | The standard of material and energy flow accounting (MEFA; Fischer-Kowalski et al., 2011; EUROSTAT, 2001) throughout the study | Data quality |
| Nasiri *et al*., (2021) | Finland | National | 2017 | Official statistical data | The MS analysis focused on Attached and Detached Houses (AADH | Bottom-up material Stock approach of Muller (2006) | Data quality |
| Aggestam & Giurca (2022) |  | National |  |  | Wood based value chain and pulp, paper, and paperboard | Conceptual approach | Waste stream were not included |
| Wang & Haller (2024) | Germany | National | 1991-2020 | Official statistical data | Physical flow of wood based products | Dynamic material flow analysis | Limited data provided |
| Kalcher *et al*., (2017) | Austria | National | 2012-2100 | Research literature and Official statistical data | They assume correlations between population growth, new construction and demolition, and use population, service stock per capita, lifetime distribution and material intensity per service unit as external functions. | Dynamic material flow analysis model presented by Muller, (2005) |  |
| Suter *et al*., (2017) | Switzerland | National | 2011 | Research literature and Official statistical data | Production to semi-finished products | Dynamic material flow analysis model presented by Muller, (2005) |  |
| Mehr *et al*., (2018) | Switzerland | National | 2016-2216 | Research literature and Official statistical data | Annual domestic wood supply of switzerland is the key input parameter to wood flow model. Availability is based on harvested wood amounts from 2015 (FOEN, 2015), excluding amount of pulp and paper. | Dynamic material flow analysis model presented by Muller, (2005) |  |
| Kanianska *et al*., (2011) | Slovakia and Czech Republic | National | 2007 | Official statistical data | Domestic Extraction, import and export of natural resources. | Economy-wide material flow analysis (EW - MFA) | They did not take into account the unused biomass |
| Wiedmann *et al*., (2023) | Switzerland | National | 2016-2019 | Official statistical data | Domestic Extraction (DE), Import (IMP) and Export (EXP) flows, and on Domestic processed output (DPO), Direct material input (DMI), the Domestic Material Consumption (DMC), and the Physical Trade Balance (PTB). | Economy-wide material flow analysis (EW - MFA) | 1) The Sum of cantonal IMP and EXP flow are not comparable with the Swiss- EW-MFA because the regional case study includes intra-national trade. 2) the lack of knowledge about inland trade between Swiss Cantons gas strong consequences on the determination of other indicator such as PTB, and DMC. |
| Lenglet *et al*., (2017) | France | National | 2009-2020 | Official statistical data | All log product as well as energy wood, sawmill residues, pulp and paper products and niche products such as wood staves. | French Forest sector model. | The final use product were not considered |
| Aryapratama & Pauliuk (2019) | Indonesia | National | 1961-2016 | Official statistical data | Wood flows from the extraction until the intermediary wood products, intermediary wood processing to the end-use of wood products; except for paper products. | Inflow-driven dynamic stock modeling (Liu and Muller, 2013; Muller et al., 2011) | Wood waste flow are not taken into account. |
| Aryapratama & Pauliuk (2022) | Indonesia | National | 1961-2016 | Official statistical data | Life cycle inventory data of forestry harvesting machinery emission. | Inflow-driven dynamic stock modeling (Liu and Muller, 2013; Muller et al., 2011) | Wood waste flow are not taken into account. |
| Johansen *et al*., (2017) | Norway | National | 2013 | Research literature and Official statistical data | Forest resources, transporation distances, road capacities, and related costs and perameters were calculated using model developed by SINTEF and real data. | Input and output Analysis introduced by Leontief (1936) |  |
| Fujino & Hashimoto (2023) | Japan | National | 1960-2000 | Grey literature and Oficial statistical data | production, products, byproducts, wastes, and resources | Input and output Analysis introduced by Leontief (1936) |  |
| Eker & Acar (2019) | Turkey | National |  | Official statistical data | Wood raw material; Sources, wood supply, processing of wood, product range, and wood consumption amount | Material flow analysis (MFA) (Fisher-Kowalski, 1998) |  |
| Brownell *et al*., (2023) | Denmark | National | 2018 | Official statistical data | Harvest, import, export, and domestic flows through the bioeconomy. | material flow analysis (MFA) as described by Brunner and Rechberger (2016) | More precise data |
| Binder *et al*., (2004) | Switzerland | National | 1995 | Physical data collection and Official statistical data | Roundwood, pulpwood, and firwood and their flows | material flux analysis (MFA) and Agent analysis. |  |
| Müller *et al*., (2004) | Switzerland | National | 1900-2100 | Official statistical data | Timber chain | MFA as described by (Baccini and Brunner 1991; Baccini and Bader 1996) | Data quality |
| Gonçalves *et al*., (2021) | Portugal | National | 2015 | Physical data collection and Official statistical data | Paper, wood panels, furniture, carpentry, packaging, other woodwork, and energy (Firewood, pellets, charcoal, electricit, heat) | MFA as described by (Brunner and Rechberger, 2004) | Product use data were not available and some othere data quality were assumpted. |
| Las Heras Hernández (2021) | Norway | National | 2020 | Survey and reports | Sawmill company | MFA as described by (Brunner and Rechberger, 2004) | Limited data provided |
| Layton *et al*., (2021) | France | National | 2013-2019 | Physical data collection and Official statistical data | Maritime pine flow | MFA as described by (Brunner and Rechberger, 2004) | second and third transformation industries are not included in the modelling |
| Hurmekoski *et al*., (2023) | Finland | National | 2020 | research literature and Official statistical data | Logs, pulpwood, and energy wood | MFA as described by (Brunner and Rechberger, 2004) | A systematic approach is required to for reliably indentifying subtitute products and services, as well as the rate of substitution. |
| Szichta *et al*., (2022) | Germany | National | 2019 | Detailed survey, Grey literature, and Official statistical data | Physical flow of wood based products | MFA as described by (Brunner and Rechberger, 2017) |  |
| Hashimanto & Moriguchi (2004) | Japan | National | 1995 | Official statistical data |  | MFA as descriped by Ayres (1998) |  |
| Kayo *et al*., (2019) | Japan | National | 1970-2050 | Official statistical data | Wood flow includes wood fuel, processing residues and waste woods | MFA as descriped by Ayres (1998) |  |
| Parobek *et al*., (2014) | Slovakia | National | 2011 | Physical data collection and Official statistical data | Roundwood production and imports, Roundwood consumption and export, and recycled material. | Physical -based accounting approach | Data quality |
| Kalt (2015) | Austria | National | 2011 | Expert opinion, Grey literature, and Official statistical data | Biomass processes upto end use product | Physical -based accounting approach | Data Quality |
| Parobek & Paluš (2016) | Slovakia | National | 2013 | Official statistical data | Primary wood processing flow | Physical -based accounting approach |  |
| Iost *et al*., (2020) | Germany | National | 2015 | Official statistical data | Agriculture biomass, Forest biomass, and Aquatic biomass. In each sector they include the production to final use products. | Physical -based accounting approach | Data gaps |
| Silva *et al*., (2020) | Brazil | National | 2008-2018 | Official statistical data | Wood based material and energy | Physical -based accounting approach |  |
| Bösch *et al*., (2015) | Germany | National | 2010 | Research literature and Official statistical data | Sawnwood, wood-based panels, processed wood products as well as pulp, paper, paperboard and printed matter. | Physical Input and Output table (PIOT) |  |
| Bösch *et al*., (2017) | Germany | National | 2014-2048 | Expert opinion, Grey literature, and Official statistical data | Roundwood and fuel wood | Physical Input and Output table (PIOT) |  |
| Delahaye *et al.,* (2023) | Netherland | National | 2018 | Official statistical data | The table will discribe the supply and use of goods and services are published for 95 commodities in 81 sectors | Physical Supply use table | Data quality |
| Suomalainen (2012) | Switzerland | National | 2000 and 2010 | Official statistical data | entire supply chain | Stock and Flow model is an adaptation from the Faist Emmenegger & Frischknecht (2003) | Data Quality |
| Hekkert *et al*., (2000) | Netherland | National | 1990 | Official statistical data | Paper and wood products | STREAMS | Data quality, waste stream were not taken into account because of no monetory value, no recycling stream data were available. |
| Babuka *et al*., (2020) | Czech Republic | National |  | Research literature and Official statistical data | Wood impregnation, roundwood, veneer, plywood, Oriented strand boards, particleboards, MDF, pulp, and energy production. | The methodology of lenglet et al (2017) was followed and the cascading approach to wood flow analysis introduced by Mantau (2015) was applied. | Data quality, and wood for energy is not considered |
| Bilot *et al*., (2023) | France | National | To develop a bottom-up modeling approach for the wood fuel and supply chain (WFC). | Survey and reports | Two segments are defined within the WFC; The forest harvesting segment and Processing. | The wood flow and supply chain (WFC) model approach is inspired by work studies (IUFRO 1995) |  |
| Cheng *et al*., (2010) | China | National | 1953-2000 | Grey literature and Official statistical data | Natural resources, Raw material, Intermediate product, Final product, Residues and wastes |  |  |
| Émilien (2023) | Norway | National | 2022 | Survey and Reports | Complete flow of paper up to recycling. |  | The study does not account for variation in paper production. |
| Schweinle *et al*., (2020) | Germany | Product | 2010 and 2015 | Official statistical data | Product (Pallet) with different uses, lifetimes, recycling rates | Economy-wide material flow analysis (EW - MFA) | Lack of data |
| Ebrahimian & Mohammadi (2023) | Sweden | Product | 10 years | Research literature and Official statistical data | entire supply chain | material flow analysis (MFA) as described by Brunner and Rechberger (2016) |  |
| Sevigné-Itoiz et al., (2015) | Spain | Product | 2006-2011 | Official statistical data | Life cycle of paper and board from production to recovered paper | MFA as described by (Brunner and Rechberger, 2004) | Data quality |
| O'Brien & Bringezu (2018) | EU-27 | Regional | 2002-2011 | Official statistical data | Roundwood production, removals, processed products, import and export of wood products. | Economy-wide material flow analysis (EW - MFA) | Gaps, Uncertainty, and a lack of harmonization regarding especially trade data. Recyceled and recovered flows were not taken into account. |
| Zhu *et al*., (2023) | Eastern Europe (Bulgaria, Croatia, Poland, and Romania) | Regional | 1990-2019 | Research literature and Official statistical data | Biomass, Metals, Non-metallic minerals, and Fossil materials. | Inflow-driven dynamic stock modeling (Liu and Muller, 2013; Muller et al., 2011) | Poor Data quality for circularity assessment. Recycling definition should be clear in the policies for specific industries. |
| Bais-Moleman *et al*., (2018) | EU-28 | Regional |  | Research literature and Official statistical data | Round production and consumption, the sawmill process, the post consumer waste recovery process, pulp and particleboard manufacturing processes and transport. | Material and Energy flow accounting |  |
| Andreadou (2023) | Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Lithuania, Netherland, Norway, Poland, Spain, Swedan and Switzerland | Regional | 90 companies across the Europe | Survey and reports | All the relevent information about the company | Material flow cost accounting |  |
| Mancini *et al*., (2015) | EU-27 | Regional | 2000-2010 | Official statistical data |  | MFA as described by (Bringezu and Moriguchi, 2002; OECD, 2008). |  |
| Mantau (2012) | EU-27 | Regional | 2010 | Official statistical data | Wood flows from production of semi-finished products, and Finished products and also paper and recovered paper were included. | Physical -based accounting approach |  |
| Mantau (2015) | EU27 | Regional | 2010 | Detailed survey, Grey literature, and Official statistical data | Wood industry, pulp industry, Biomass power plant, Households, Pellets | Physical -based accounting approach |  |
| De Laurentiis *et al*., (2022) | EU27 | Regional | 2018; And temporal resolution 2014 to 2019. | Official statistical data | Land footprint: Cropland, grassland, forest land, Agriculture land, Arable land, permanent land, urban and artificial land, built-up land | Physical -based accounting approach |  |
| Wang *et al*., (2020) | 13 cities in the Beijing-Tianjin-Heibei region of China | Subnational | 2017 | Research literature and Official statistical data | Biomass, metallic minerals, non-metallic minerals, industrial products, fossil fuels and verious types of pollutants and wastes. | Bottom-up accounting framwork for Urban material flow analysis | Data quality |
| Nikodinoska *et al*., (2017) | North Italy | Subnational | 50 years | Survey and reports | Forestry, Logistics and Conversion | Material and Energy flow accounting |  |
| Cammack (2023) | Orchid City in Netherland | Subnational |  | Research literature and Official statistical data | wood based value chain | material flow analysis (MFA) as described by Brunner and Rechberger (2016) | Data quality |
| Cordier *et al*., (2019) | Quebec, Canada | Subnational | 2010-2050 | Official statistical data | Domestic Harvesting, transforming (1st and 2nd), manufacturing of structural products, and using those product. The material losses from the first transformation are included. | Material flow analysis (MFA) as described by Sandberg and Brattebo (2012) |  |
| Ilc (2016) | Slovakia, Italy and Austria | Subnational | 2008-2014 | Research literature and Official statistical data | Forestry: Removal, production and trade | material flux analysis (MFA) and Agent analysis. |  |

**Table 2.** A summary of the methodological approaches used in the literature review

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Approaches** | **Definition** | **Description** | **Uses** | **Example** |
| Material flow Accounting (MFAc) | Core component of MFA focusing on the systematic accounting of material input, output, and stock within a defined system. | Tracks and analyses the movement of materials through a system, considering inflows, outflows, and accumulation of material stocks, offering insight for resource management and industrial ecology. | Used in sectors like forestry, bioenergy, and wood-based value chains to analyze material flows and environmental impacts. | [42] applied MFAc and LCA in EU for wood-based value chain; [43] in North Italy for bioenergy sector analysis. |
| Bottom-up Material Stock Analysis (MSA) | A detailed method that examines individual material stocks, starting from end-products and tracing back to input materials and flows. | Focuses on specific sites or projects, using detailed data about material composition, quantity, and location to estimate total stocks and flows. Enable a granular analysis of material efficiency and flow dynamics. | Used for analyzing site-specific industries such as wood fuel supply chains and construction materials. | [48] used MSA in France to analyze wood fuel supply chain; [49] used it for MFA in 13 cities in China. |
| Physical Accounting | Quantitative and integrated analysis of material, energy, and waste flow. | Build on the entropy law, creating frameworks for national accounts like NFA and MEB. Focuses on holistic physical environmental accounting, including material flow and mass balance, often integrated with EMA. | Tracking material and energy at national or industrial levels for sustainability and resource management. | [53] applied this in the Slovakian wood industry; [54] used it to assess biomass flows in Austria. |
| Material Flow Cost Accounting (MFCA) | A specialized EMA method that traces and quantifies material flows and their costs and within an organization. | MFCA allocates costs to products/services based on material flows and waste generation. Helps businesses reduce waste and improve both financial and environmental performance by identifying inefficiencies. | Widely used in manufacturing and industries with complex resource and waste streams for optimizing environmental and financial performance. | [66] employed MFCA to improve performance across EU companies; originated from Kunert in Germany in the 1980s, formalized under ISO 14051. |
| Input-Output Analysis (IOA) | A technique that examines the interdependencies and relationship between different sectors and industries in an economy. | Tracks the flows of materials, energy, and waste across sectors, providing detailed accounting of inputs, processes, and output within a system boundary. | Analyzing sectoral interaction and understanding how material, energy, and waste move through the economy. | [74] used IOA for wood-based product analysis in construction and waste management in Germany. |
| Economy-Wide Material flow analysis (EW-MFA) | Application of IOA on a macro scale, focusing on material flows across entire economies rather than specific sectors. | Tracks the total inputs, outputs, and material mass balances within a national economy, including extraction, trade, consumption, and waste. Provides a comprehensive view of resource use and efficiency across a country or region. | Used for national-level studies on material use, resource management, and sustainability policy. | [78] studied wood flow patterns in the EU-27 using EW-MFA; [80] analyzed material efficiency in Switzerland. |
| Environmentally extended Input-Output Analysis (EE-IOA) | An extension of traditional IOA that incorporates environmental impacts, such as energy use, emissions, and resource consumption, into MFA | Integrates economic and environmental data to evaluate the environmental impacts of economic activities and consumption patterns. Combines material flows with factors like emission, energy use, and pollutants to assess sectoral sustainability. | Often used for environmental impact assessment of industries, integrating the LCA principles with sectoral economic analysis. | [81] used EE-IOA in Germany to analyze wood-based material flows and their environmental impacts. |
| Generalized Forest Product Model (GFPMX) | Models’ material flows within forest-based industries | Forecasts consumption, production, import, export, and price of various forest products. | Understanding supply chain dynamics and policy impacts on forest product markets. | Impact of COVID-19 on the global forest sector [90]. |
| French Forest Sector Model (FFSM) | A recursive bio-economic model analyzing the interaction between the biological and economic dynamics of the French forest sector. | Combines forest dynamics (Tracking stock and growth) with market modules (focusing on supply and demand for wood), simulating economic drivers. | Policy evaluation, climate policy, and resource management. | [8, 91, 92] |
| Material flow and Agent Analysis | An MFA approach that examines how different agents shape material flows within a system. | Focuses on the influence of various agents (Producers, consumers, policymakers) and their interaction on material flow patterns and resource use. | Sector-specific resource management and policy impact analysis. | [95] |
| STREAM (Spatial and Temporal Resource Assessment) | A methodology focusing on the spatial and temporal aspects of material flow analysis. Particularly at regional or local levels. | Tracks the distribution and temporal changes of material flows and stocks in specific regions or product life cycles, like wood-based products. | Regional/local assessment, wood-based product analysis, circular economy evaluation. | [105, 106] |