MASTER'S THESIS

Global Forest Footprints of Household Consumption

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Global Forest Footprints of Household Consumption

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Global Forest Footprints of Household Consumption
Mondiale Bosvoetafdrukken van Huishoudconsumptie

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Foreword

Ever since I was a child, I have been fascinated by the wonders of nature. I always loved being in nature and studying the uncountable different forms of life surrounding us. Growing up, however, I also increasingly realized how human actions continue putting pressure on our valuable environment, from local waste to global climate change. This ultimately led me to start a bachelor in Environmental Sciences, hoping to someday be able to make a positive contribution. After multiple years of studying, I am happy finishing my Master's degree with a thesis on the interesting topic of global timber and forestland footprints. This is a very relevant subject considering the calls for increased biomass use in the context of ongoing global deforestation and forest degradation.

I am thankful for being given the chance to conduct this research, which was done in the context of the SYMOBIO project on monitoring and modelling the bioeconomy (grant no. 031 B0281A). This work allowed me to study a major environmental topic, while combining this with my passion for programming and further extending my set of skills. Ultimately, this research has been a very educational experience, and I hope its results can provide a positive contribution to reducing the consumption-driven impacts on global forest ecosystems.

At the same time, the past year has been one of the most difficult moments in my life. I have been faced with some demanding challenges in my family throughout the year. On top of this, Russia started an atrocious and needless war in my partner's home country of Ukraine. However, amid all this turmoil I am glad to now have finished this thesis.

Luckily, I was not alone during this difficult period, and I am grateful to all the people who offered support. I would like to thank my supervisor, Gibran Vita, for giving me the opportunity of working on this interesting project and for his support throughout the research. He always gave me good advice and encouraging words, but also provided me a sympathetic ear over the past year. I thank my parents for believing in me, for always being there for me during this study, and for making environmental consciousness part of my upbringing. They encouraged me to get through this thesis and endured my complaints when I was stuck with my coding. Lastly, I want to thank my partner Olia. Despite her own struggles during these times, she always provided me with support and the right words when I needed them.

Yentl Staelens

Bornem, Belgium, July 1, 2022.

Abstract

Consumption and other human activities are causing large forest losses, threatening global forest biodiversity and ecosystem services. Through globalized supply chains, timber harvests and forestland use became embodied in the consumption of goods and services. Concurrently, spatial separations between consumption and production increased, causing global displacements of impacts. A renewed striving towards expanding the bioeconomy furthermore risks exacerbating global impacts on forests.

This study aims to provide insights into the global environmental pressures exerted upon forests through timber and forestland embodied in nations' household consumption, presenting results which can inform policy towards a sustainable bioeconomy. For this purpose, forest footprints of global household consumption were analyzed using EXIOBASE 3.8 for multi-regional input-output analysis. This database covers 200 product categories and 49 regions, including the EU, major economies and 5 Rest of World (RoW) regions over the period 1995 to 2011.

Contrary to the growing biomass and mineral footprints, the global household timber footprint decreased by 4% to 2158 Mm^3, while the forestland footprint decreased by 8% to 1327 Mha. This is mainly driven by reductions in fuelwood consumption for shelter products, as both consumption of all other product categories and industrial roundwood use increased. Fuelwood drives 52% of the global footprint, mainly in lower-income countries.

RoW Africa, China, USA, Brazil and Russia cause 57% of the global household timber footprint (average 0.58 m^3/cap). Russia, RoW Africa, RoW America, China and Brazil cause 64% of the global household forestland footprint (average 0.3 ha/cap). Although especially per capita timber footprint size is associated with income (e.g. Scandinavia, Canada, Austria), large consumers such as Russia and Brazil stress additional importance of resource availability and lifestyles. Differences between both footprints signal varying timber productivity.

Net exporters of forest footprints are generally abundant in forest resources (e.g. Canada, Sweden, RoW Africa, Russia), while net importers are industrialized or emerging economies (e.g. Japan, USA, Germany, India, China). Most regions increased their displacements abroad, with average displacements of 48% for timber and 52% for forestland footprints (both +10%), and the largest footprint displacements occurring in high-income regions. Within the EU, increased internal trade could partially explain these trends as the EU's displacements strongly decreased (-44% timber, -40% forestland). Higher dependencies on foreign forestland suggest common outsourcing to less productive regions.

Ten products represent 79% of household timber and 82% of household forestland footprints, with little-processed wood products contributing the most. On average 48% (timber) to 49% (forestland) of the footprints were related to shelter products. While shelter shares decreased with income, especially manufactured products (15% average) and services shares (11% average) increased.

Compared to productivity figures, opportunities for woody bioeconomy growth seem limited. Particularly harvests in Brazil and Africa are likely unsustainable, but still embodied in household consumption. A fair bioeconomy requires continuous monitoring of the footprints, applying well-developed reference levels for sustainable consumption of global resources. In developing countries, access to modern energy and household appliances will be important, while in general increased cascading with material uses preceding energy recovery seems key to reducing global impacts on forests.

Samenvatting (Dutch abstract)

Consumptie en andere menselijke activiteiten veroorzaken grote verliezen aan bosland, en bedreigen de wereldwijde biodiversiteit en ecosysteemdiensten van bossen. Door de globalisering van toeleveringsketens geraken houtoogsten en bosland ingebed in de consumptie van goederen en diensten. Tegelijk namen ook de ruimtelijke scheidingen tussen consumptie en productie toe, met verplaatsingen van impacts tot gevolg. De hernieuwde aandacht voor de bio-economie dreigt de wereldwijde impacts op bosecosystemen verder te vergroten.

Deze studie heeft tot doel inzicht te verschaffen in de mondiale milieudruk op bossen als gevolg van de houtoogsten en het bosland ingebed in wereldwijde huishoudconsumptie, waarbij de resultaten het beleid kunnen informeren richting een duurzame bio-economie. Daartoe werd EXIOBASE 3.8 gebruikt voor de multiregionale input-outputanalyse van bosvoetafdrukken van huishoudens wereldwijd. Deze database omvat 200 productcategorieën en 49 regio's, waaronder de EU, de belangrijkste economieën en 5 Rest-van-de-Wereld (RvW) regio's over de periode 1995 tot 2011.

In tegenstelling tot de toenemende biomassa en minerale voetafdrukken, daalde de hout-voetafdruk met 4% tot 2158 Mm^3, terwijl de bosland-voetafdruk daalde met 8% tot 1327 Mha. Dit werd vooral veroorzaakt door dalend energiehoutgebruik van huisvestingsproducten, terwijl de consumptie van andere productcategorieën en industrieel rondhout toenamen. Energiehout is goed voor 52% van de wereldwijde bosvoetafdruk, vooral in lagere-inkomenslanden.

RvW Afrika, China, de VS, Brazilië en Rusland veroorzaken 57% van de wereldwijde houtvoetafdruk van huishoudens (gemiddelde 0.58 m^3/cap). Rusland, RvW Afrika, RvW Amerika, China en Brazilië veroorzaken 64% van de wereldwijde boslandvoetafdruk van huishoudens (gemiddelde 0.3 ha/cap). Hoewel vooral de per capita houtvoetafdrukgrootte is geassocieerd met inkomen (e.g. Scandinavië, Canada, Oostenrijk), tonen grote voetafdrukken in Rusland en Brazilië aan dat ook de beschikbaarheid van hulpbronnen en de leefstijl van invloed zijn. Verschillen in beide voetafdrukken wijzen op variaties in houtproductiviteit.

Netto-exporteurs van bosvoetafdrukken zijn over het algemeen rijk aan bossen (e.g. Canada, Zweden, RvW Afrika, Rusland), terwijl net-importeurs geïndustrialiseerde of opkomende economieën zijn (e.g. Japan, VS, Duitsland, India, China). Verplaatsingen van voetafdrukken naar het buitenland namen toe, met een gemiddelde afhankelijkheid van verplaatsing van 48% voor de houtvoetafdruk en 52% voor de boslandvoetafdruk (+10%), en de hoogste afhankelijkheden in hoge-inkomenslanden. Binnen de EU hangen deze trends waarschijnlijk gedeeltelijk samen met hogere interne handel, gezien de sterke daling van EU voetafdruk-verplaatsingen (-44% hout, -40% bosland). Hogere afhankelijkheden van buitenlands bosland suggereren dat productie vaak wordt uitbesteed naar landen met lagere productiviteit.

Tien producten veroorzaken 79% van de houtvoetafdrukken en 82% van de boslandvoetafdrukken, vooral door houtproducten. Gemiddelde zijn 48% (hout) tot 49% (bosland) van de voetafdrukken gerelateerd aan huisvestingsproducten. Terwijl deze aandelen dalen met het inkomen, stijgen voornamelijk gefabriceerde producten (15% gemiddelde) en diensten (11% gemiddelde) in belang.

Vergeleken met productiviteitsschattingen lijken de mogelijkheden tot groei van de hout-bio-economie beperkt. Vooral houthak in Brazilië en Afrika zijn waarschijnlijk niet-duurzaam, maar alsnog ingebed in de huishoudconsumptie. Een eerlijke bio-economie vraagt continue monitoring van voetafdrukken, waarbij goed-ontwikkelde referentieniveaus voor duurzame consumptie van wereldwijde hulpbronnen worden aangehouden. In ontwikkelingslanden is toegang tot moderne energie en huishoudapparaten van belang, terwijl meer algemeen toegenomen cascadering met materiële toepassingen gevolgd door energieterugwinning van belang lijkt voor de beperking van wereldwijde impacts op bosecosystemen.

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1. Introduction

Forests form an essential part of the world's ecosystems. In 2020, they were estimated to cover about 31% of the land area, for a total of 4.06 billion hectares (FAO, 2020b). Forests provide important habitats for many species, including 68% of mammals, 75% of birds and 80% of amphibians (Vié et al., 2009). Such biodiversity ensures a variety of provisioning and regulating ecosystem services, with more than two billion people estimated to be dependent upon forests and their resources (FAO & UNEP, 2020).

These rich forest ecosystems are however under pressure because of activities such as forestry, shifts in agricultural activities and permanent conversion to produce various commodities (Curtis et al., 2018). As a result, the global forest area decreased by 178 million hectares since 1990, with an average loss of 4.7 million hectares per year between 2010 and 2020 (FAO, 2020b).

Forest degradation and deforestation cause social and environmental impacts in multiple ways. It harms biodiversity, especially in natural forests such as found in the tropics (Purvis et al., 2019). Forest loss impacts climate change as deforestation is a major source of CO_2-emissions, while reducing the carbon sequestration potential, and changing the regional climate (FAO, 2020b; IPCC, 2019). Furthermore, it affects the well-being of the many people who depend on forest biodiversity and ecosystem services to provide necessities such as food, medicines, energy and income (FAO & UNEP, 2020).

At the same time, these impacts are not equally spread across the globe. While Eurasian forest area losses have been countered by gains, large losses of forest area occur in multiple areas, and particularly in tropical regions (Hansen et al., 2013). Deforestation in these regions shifted from small-scale farming to forestry and agricultural operations serving international markets, which expanded due to globalization (Meyfroidt et al., 2013).

Such impacts driven by international trade are common in a tele-coupled world, where interactions occur between distant socioeconomic and natural systems (Liu et al., 2013). In the case of biomass, increasing trade has caused considerable spatial separations of the locations where biomass is produced and consumed (Erb et al., 2009). Distant production within increasingly globalized supply chains causes displacement of social and environmental impacts, away from the points of consumption (Wiedmann & Lenzen, 2018). Although not physically traded, impacts generated by production industries are linked to trade flows through supply chains, and become embodied in the final consumption of products (Wiedmann & Lenzen, 2018).

As a result of this, impacts on forests in the form of timber harvests, associated use of forestland and overall deforestation activities have become embodied in the consumption of commodities and services (Hoang & Kanemoto, 2021; O'Brien & Bringezu, 2018; Yu et al., 2013; Zhang et al., 2020). Upstream embodied impacts can be associated to downstream consumption activities of different end-users (Wiedmann & Lenzen, 2018). Households form particularly important end-users, as their consumption is responsible for between 50 and 80% of the greenhouse gas emissions, and land, water and material use (Ivanova et al., 2016). Yet, not much is known about global households' impacts on forests, and the specific products driving these impacts.

Concurrently with the increasing globalization, a worldwide expansion of the bioeconomy is ongoing, in which biological resources are utilized to provide a variety of products and services (von Braun, 2018). The European Union and multiple Member States (European Commission, 2018; French Ministry of Agriculture and Food, 2017; German Federal Government, 2020; Italian Government, 2019) are all striving towards increased biomass use as part of their bioeconomy strategies. The use of bioenergy is meanwhile seen as an option to mitigate climate change (IEA, 2017; Rogelj et al., 2018). Such grand expectations for the bioeconomy risk putting more pressure on global forests, as the question arises how this demand can be met sustainably.

Research to footprints enables the analysis of global embodied impacts (Wiedmann & Lenzen, 2018). More specifically, impacts and sustainability of timber consumption can be studied through footprints in terms of land and volume (Egenolf & Bringezu, 2019). Yet, the research on global forest footprints is currently limited, particularly regarding household consumption.

Timber footprints at the global level have received little attention (e.g. Zhang et al., 2020), with most studies instead focusing on a single region (e.g. Egenolf et al., 2021; Liang et al., 2016; O'Brien & Bringezu, 2018). Although generally global, forestland footprint studies often aggregate different types of land uses (e.g. Lugschitz et al., 2011; Weinzettel et al., 2013; Wilting & Vringer, 2009) or have limited attention for forestland specifically (de Laurentiis et al., 2022; Fischer et al., 2017; Yu et al., 2013). While household consumption has important environmental impacts, and knowledge thereof can help shape household actions and policy to reduce impacts (Ivanova et al., 2016; OECD, 2011), forest footprint studies generally consider only total final demand. Driving sectors for forest footprints also received limited coverage (e.g. Fischer et al., 2017; Liang et al., 2016; Lugschitz et al., 2011; Yu et al., 2013).

Still missing is a study on the timber volume and forestland embodied in global household consumption and resulting international trade, with attention to driving sectors. Studying both can however provide a clear picture, as the volume relates to overall sustainability as well as impacts on carbon storage, while forestland reflects biodiversity and ecosystem services impacts. Furthermore, the limits of the chosen input-output analysis method for forest footprints can be explored.

This descriptive and explorative study aims to give insights into the global environmental pressures exerted upon forests through the timber and forestland embodied in the consumption of various products by households worldwide. The results of this research can inform both policy and households towards a more sustainable woody bioeconomy. To be more relevant for European bioeconomy strategies, additional attention will be given to footprints in the European Union. To achieve these aims, forest footprints are quantified in terms of the volume of timber and area of forestland required to satisfy the consumption of households over time. By analyzing the flows of timber and forestland in the global economy, the largest product sectors and nations driving the use of forest resources as well as the important sourcing nations are identified.

The research attempts to answer the following main research question:

- ***How do the forest footprints of timber and forestland embodied in household consumption and the role of international trade therein compare over time and between regions, and which products are driving these footprints?***

Based on this main question, the following sub-questions are distinguished:

- *How did the global forest footprints of household consumption change over time, and which regions are the major consumers, importers and exporters of embodied timber and forestland?*
- *How do the regional per capita forest footprints of household consumption compare over time?*
- *Which product categories are the most important drivers of the forest footprints?*

2. Literature review

2.1. Consumption of forest resources and the loss of forest area

While the net observed forest loss continues (FAO & UNEP, 2020), ambiguity exists in literature on the definitions of forests and deforestation (Fernández-Montes de Oca et al., 2021). It is hence important to specify what is meant by forests, forest loss and deforestation.

A lot of the literature relevant to forest footprints (e.g. Egenolf et al., 2021; Liang et al., 2016; Weinzettel et al., 2013; Yu et al., 2013; Zhang et al., 2020) uses data from FAOSTAT directly or through databases. Hence, the FAOSTAT definition of forests forms a good starting point, as previously used in the Global Forest Resources Assessment (FAO, 2020b). Forests then consist of "land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ" (FAO, 2018, p. 4). They exclude predominately urban and agricultural areas such as fruit tree plantations and agroforestry systems with crops (FAO, 2018, p. 4).

Between 2010 and 2020, the global average net loss of forests was 4.7 million hectares per year, a decrease from the averages of 5.2 million hectares per year in the 2000s and 7.8 million hectares per year in the 1990 (FAO, 2020b). This slow-down in loss is related to reduced deforestation, natural regrowth and afforestation efforts (FAO, 2020b). Loss of forest area can result from permanent conversion (e.g. for agriculture or infrastructure), or from forestry, temporary agriculture and wildfires, the latter three still allowing regrowth (Curtis et al., 2018). However, even if not lost, forest degradation affects the structure and functioning of forests, and hence its provisioning of ecosystem services (Fernández-Montes de Oca et al., 2021).

According to the definition of the Global Forest Resources Assessment (FAO, 2020b, p. 13), deforestation occurs when forests are transformed to other land uses. Net forest losses then refer to a situation where the balance between deforestation and natural or managed regrowth is negative (FAO, 2020b, p. 13). This explains why the annual average deforestation rate of 10 million hectares (2010-2015) is much higher than the global net forest area loss (FAO, 2020b).

The forest footprints in this thesis resemble timber harvests by the forestry sector to satisfy global household consumption. Thus, they will include a mix of deforestation through permanent land use change and harvests in managed forestry areas where regrowth is possible. As Pendrill, Persson, Godar and Kastner (2019) note, it is difficult to quantify the deforestation impacts from timber harvests, because there is no clearly defined successive use of this land. Nevertheless, forestry is found to contribute to global deforestation and forest degradation, with particularly in the tropics more than 60% driven by agricultural and forest products (Hoang & Kanemoto, 2021; Pendrill, Persson, Godar, & Kastner, 2019). Forestry activities are major disturbers of forests, causing about 26% of the global tree cover loss between 2001 and 2015 (Curtis et al., 2018). As a result, timber harvests are responsible for most of the forest degradation (Purvis et al., 2019).

The utilization of forest products can be both about wood and non-wood products. According to the Global Forest Resources Assessment (FAO, 2020b), almost half of the non-wood products consist of food such as fruits, vegetables, honey, mushrooms and wild meat, while raw materials for utensils and medicines are also common forest products.

Wood removals in 2018 amounted to 3.97 billion m^3, requiring an estimated 1.15 billion hectares of primarily productive forestland with an additional 749 million hectares of forests potentially in use for this purpose (FAO, 2020b). The shares of industrial wood and fuelwood in wood removals are both about 50% (FAO, 2020b). Fuelwood refers to wood harvests for the purpose of heating, cooking and power (FAO, 2020a, p. 25). It includes wood and wood chips used as fuel for cooking, heating and power generation, and for producing agglomerates such as wood charcoal and pellets. Industrial roundwood refers to harvested wood used for other purposes than fuel (FAO, 2020a, p. 25).

Wood statistics further divide this into coniferous or 'softwood' and non-coniferous or 'hardwood'/broadleaf types (FAO, 2020a, p. 25). Coniferous types dominate in European and North- and Central American countries, while non-coniferous growing stocks dominate South America, Africa and Oceania (FAO, 2010a). As Lauri et al. (2021) note, timber harvests are shifting from coniferous to non-coniferous types through the development of a globalized forestry industry, because the large western forestry industry was initially dependent on its own coniferous timber.

2.2. Environmental impacts of forestry activities

Human influences and increasing management have caused many natural intact forests to disappear or degrade. Almost all temperate forests and two-thirds of boreal forests are now managed, while biodiversity-rich tropical forests continue declining (Purvis et al., 2019).

A major effect of timber harvests and land use change is the reduction of old-growth forests worldwide, with young and less diverse forests increasing to a third of the total forest area (McDowell et al., 2020). High disturbance can cause slow and more homogenous succession of secondary forests, impacting biodiversity, in particular native specialist species, as well as the potential for providing ecosystem services (Arroyo-Rodríguez et al., 2017). Intact forests provide more resilient and larger habitats, increasing forest-dependent species, diversity in species with different ecosystem functions and genetic diversity within species (Watson et al., 2018).

In tropical areas, which are under pressure because of extensive deforestation, both animal and plant biodiversity is reduced, with some species even risking extinction (Alroy, 2017). In temperate forests, 35 million hectares of intact primary forest was transformed into less biodiverse secondary forests between 2000 and 2013, while invasive species further increase pressures (Purvis et al., 2019). In Mediterranean forests, the sensitivity to external factors (e.g. human influence, climate, fire) poses an important threat to its biodiversity (Purvis et al., 2019).

Literature has already linked global supply chains, and often particularly agricultural and forestry commodities, to biodiversity impacts (Chaudhary et al., 2017; Marques et al., 2019) and hotspots of threatened species (Moran & Kanemoto, 2017).

Similarly, consumption-driven forest loss is linked to climate change impacts. The forest growing stock volume of forests is often related to the available forest biomass and its carbon stocks, which provide an indicator for the carbon sequestration of forests (FAO, 2020b). Hence, timber harvests provided as volume of wood removals (e.g. FAO, 2020b) can affect the available growing stock volume. The forestry sector has been found to globally cause the largest losses of potential carbon sequestration, at about 1 gigaton C per year, with an increasing trend (Marques et al., 2019).

While temperate and boreal forests form important sinks, tropical deforestation and degradation is a major source for greenhouse gas emissions from biomass and soil carbon stocks (Don et al., 2011; Pan et al., 2011). On average, about 2.6 gigatons of CO_2 emissions can be attributed to tropical deforestation, resulting from expanding agricultural and forestry activities (Pendrill, Persson, Godar, Kastner, et al., 2019). Overall, the total carbon stocks of forests have declined by about 6 gigatons over the last 30 years, with increases in regions like Europe and North America, and large decreases in South America and West and Central Africa (FAO, 2020b).

Importantly, degradation of forests also affects the regional climate. It impacts rainfall, temperature and overall hydrology, as well as the protection against extremes such as droughts (Watson et al., 2018).

2.3. The expanding global bioeconomy

Consumption of biomass is growing globally. The total biomass consumption increased from 9.1 billion tons in 1970 to 24.1 billion tons in 2017, with an expected increase in biomass use of 1.7% per year until 2060 (Oberle et al., 2019). Although to a lesser extent, wood harvests rose from 3.54 to 3.97 billion m^3 (+12%) between 1990 and 2018 (FAO, 2020b). Wood demand is expected to increase, possibly even doubling for energy use between 2010 and 2030 (Mantau et al., 2010). Even during the recent COVID-19 pandemic, tropical deforestation increased, while some governments used the pandemic to reduce the legal control of deforestation (Daly, 2020).

The expanding bioeconomy is meanwhile further stimulated by the extensive expectations for the bioeconomy to solve environmental problems. The EU's bioeconomy strategy (European Commission, 2018) expects increased use of renewable materials and bio-based products in various sectors, and the use of more bioenergy, to enable greenhouse gas emission reductions in line with the Paris Agreement and renewable energy commitments. The strategy sees the bioeconomy as part of a growing circular economy which reduces waste, improves ecosystem health and land degradation, and provides new jobs. For forestry products, opportunities are seen in forestry-based resources to become more sustainable and further contribute to replacing unsustainable materials (European Commission, 2018).

Bioenergy is important in the scenario of an average 2°C temperature increase by 2100 of the IEA (2017). This would require a growth of the bioenergy contribution in the final energy demand from 4.5% in 2015 to 17% in 2060. By 2060, this would then save an annual 5.7 gigatons of CO_2, with additional carbon capture systems possibly providing further reductions (IEA, 2017). Pathways of the IPCC (Rogelj et al., 2018) to limit global warming to 1.5°C all apply some extent of carbon dioxide removal, most often afforestation and bioenergy with carbon capture and storage. Bioenergy use in general plays an important decarbonizing role in modelling these different pathways (Rogelj et al., 2018). The Fifth Assessment Report of the IPCC (2014) noted that with limited availability of bioenergy, carbon capture systems, or their combination, many models failed to produce scenarios that would limit the temperature increase to below 2°C. This dependency on the bioeconomy for future scenarios has implications for worldwide policies on energy and greenhouse gas emissions.

On the national level, multiple European countries also have high expectations for the launch of their bioeconomy strategies. In France, the bioeconomy strategy sees opportunities such as improving sustainable development, finding solutions to meet climate commitments and creating jobs (French Ministry of Agriculture and Food, 2017). Similar goals are present in Italy's strategy (Italian Government, 2019), which expects an increased turnover of 15% by 2030, while specifically mentioning more attention to bioenergy from wood and use of wood within the construction sector. The German National Bioeconomy Strategy (German Federal Government, 2020), for example, also stresses the possible contribution to achieving Sustainable Development Goals (SDGs) from the UN Agenda 2030. The strategy points to a potential for 11 out of 17 SDGs, from ending hunger (SDG 2), to clean and affordable energy access (SDG 7), decent work and economic growth (SDG 8), climate action (SDG 13), and life below water and on land (SDG 14 & 15). Such expectation of the contribution of the bioeconomy to meeting SDGs also exists at the level of the EU (European Commission, 2018).

The question is whether the bioeconomy demand can be satisfied sustainably. As concluded by a UNEP (2015) report, further improvements in biomass productivity of Asian and European countries are limited, causing these regions to depend on imports. Yet, scenarios exist in which the global bioeconomy increases by almost 50% in case of a modest development, or almost doubles for a strong bioeconomy (European Commission, 2015). This would imply more forestland, both naturally regenerating and planted, to be in use for biomass production (European Commission, 2015). Ramcilovic-Suominen and Pülzl (2018) argue that the EU's strategy uses the concept of sustainability to promote the bioeconomy. However, the focus is mostly on the economic dimension of ensuring continuous resource availability for consumption and potential production increases, while environmental and social concerns are less prevalent (Ramcilovic-Suominen & Pülzl, 2018).

Boundaries to growth are seemingly lacking in the EU's strategy, despite the bioeconomy being proposed as a way to solve environmental problems (Lühmann, 2020). Hence, the grand expectations for the bioeconomy could potentially be problematic. As the bioeconomy does not automatically lead to positive effects for all SDGs either, sufficient attention to sustainability is necessary (Heimann, 2019). Considering countries can outsource environmental impacts induced by their consumption through trade (Oberle et al., 2019), this should be seen on an international level. The combination of the hope on the bioeconomy and its potential issues thus requires analyses to inform policy and warrant sustainability.

2.4. Footprint accounting for household consumption

A particular way of analyzing the pressures of human activity on the environment is through footprint accounting. Footprints form indicators for the human-induced changes to the state of the environment and its resulting impacts (Hoekstra & Wiedmann, 2014).

Well-known is the 'ecological footprint', as originally proposed by Wackernagel and Rees (1996) to express the environmental burden on the planet driven by consumption. This approach calculates hectares of land needed to satisfy consumption by combining different types of actual land use with a calculation of energy land required to counter greenhouse gas emissions. Doing so, however, specific land use details are lost, while the emission footprint as a different indicator is mixed with the actual land use. For this reason, it is useful to focus on specific footprints, which were increasingly developed over time. Examples include material (Wiedmann et al., 2015), water (Hoekstra & Mekonnen, 2012), carbon (Hertwich & Peters, 2009) and land (Weinzettel et al., 2013) footprints. As discussed further on, certain aspects of forest footprints have also received attention in literature.

Considering sustainability requires footprints to stay within safe maximum sustainable use of the environment, the concept is related to 'planetary boundaries' (Hoekstra & Wiedmann, 2014). Initially proposed by Rockström et al. (2009), planetary boundaries define threshold values for Earth-system variables beyond which subsystems or biophysical processes can shift to unfavorable or even disastrous states. Among key variables identified by Rockström et al. (2009), forest footprints particularly add pressure to global land use change and biodiversity loss. Yet, complex system interactions mean that processes, even those without distinguishable thresholds, can affect other Earth-system processes as well (Rockström et al., 2009). Sustainability of forest footprints can be assessed by comparison to the net annual increment (NAI) of a specific region (Egenolf & Bringezu, 2019). The NAI indicates forest productivity in the form of the average volumetric increase in growing stock (with or without bark), as discussed and reported on by O'Brien (2016).

Footprint accounting can be both production-based and consumption-based. Nation's production-based footprints refer to resource consumption (domestically extracted or imported for domestic production) and emissions produced within this nation (Wilting & Vringer, 2009). Consumption-based accounting shifts the responsibility to final consumers within a nation, equaling resource use and emissions from domestic and foreign production to satisfy the domestic consumption of a certain nation (Wilting & Vringer, 2009).

Such approach means 'displaced impacts' resulting from the embodied impacts in foreign production are considered (Wiedmann & Lenzen, 2018). In general, wealthier regions like Europe and North America tend to consume more resources than they produce, often outsourcing environmental impacts to developing countries (Haberl et al., 2019; Oberle et al., 2019). On a global level, between 10 and 70% of resource use and emission impacts are displaced (Wiedmann & Lenzen, 2018). Land use to produce forestry and agricultural products is also displaced abroad to satisfy household consumption (Meyfroidt et al., 2010; Yu et al., 2013), and can be specifically linked to deforestation (Hoang & Kanemoto, 2021; Pendrill, Persson, Godar, & Kastner, 2019). Increasing displacement can relieve domestic pressures on forests, as suggested by its links to forest transitions characterized by a shift towards net reforestation (Kastner et al., 2011; Meyfroidt et al., 2010).

This role of trade and embodied impacts in imports and exports makes consumption-based approaches increasingly relevant. Production-based approaches risk incentivizing further outsourcing production to improve domestic impacts and meet environmental targets (Galli et al., 2012; Wilting & Vringer, 2009). Focusing on consumption helps for identifying such displacements globally, studying the drivers for global demand, increasing international cooperation and informing sustainability policies (Galli et al., 2012; Tukker et al., 2014).

Different consumption categories can be accounted for, e.g., households, governments, non-profit organizations serving households, gross capital formation and changes in inventory. Gross capital formation can be seen as referring to fixed assets, which are goods or services used for production (United Nations et al., 2009, pp. 198–199). Changes in inventories meanwhile result from price changes of goods held in storage (United Nations et al., 2009, pp. 207–208).

Focusing specifically on household consumption can provide further relevant insights. Household consumption drives most of the material, land, water and greenhouse gas emission footprints (Ivanova et al., 2016). Consumption patterns ultimately result from behavior, which is linked to aspects such as lifestyles and routines (Caeiro et al., 2012). Drivers for behavior include basic needs or various 'wants', values inherited from society or culture and preference for immediate consumption (Thøgersen, 2014). This is further influenced by societal consumption norms, consumption habits, denial surrounding environmental issues, and financial, knowledge and other limiting factors (Thøgersen, 2014).

While policy can improve consumption sustainability through supply-side measures and economic incentives for consumers, behavioral change by providing information also plays a major role (OECD, 2011; Thøgersen, 2014). The household footprints in this research can both inform consumers to make more conscious choices as well as policy to take adequate measures.

2.5. Methods for analyzing global footprints

Two main methods, economy-wide material flow analysis (ew-MFA) and multi-regional input-output analysis (MRIO), as well as a hybrid method can be distinguished for determining global footprints.

The basis for ew-MFA was provided in 1969 by Robert Ayres and Allen Knees (Fischer-Kowalski et al., 2011, p. 857). In ew-MFA, a system is defined with specific boundaries, such as a national economy (Fischer-Kowalski et al., 2011). In- and outflows into the system are then accounted for, flowing into stocks (system compartments) where accumulation is possible. Such systems should remain balanced, with inflows equaling the outflows plus accumulations in stocks (Fischer-Kowalski et al., 2011).

The physical accounting method of ew-MFA can be used for timber flows, but also for flows of embodied forestland, as done by O'Brien and Bringezu (2018) for forest products in the EU. Accounting for forestland in ew-MFA is possible by applying a method similar to the Global Land Use Accounting performed for cropland (e.g. Bringezu et al., 2012; O'Brien et al., 2015). If the domestically consumed and traded timber volumes are known, productivity figures (NAI) can be used to calculate the forestland footprint (O'Brien & Bringezu, 2018). This so-called 'sustainable yield method' is often used for determining forestland footprints, due to the associated difficulties (Bruckner et al., 2015).

A second option is the monetary (economic) method of MRIO. Input-output analysis is known from Wassily Leontief's 1930s framework to study interindustry interactions, although its roots can be traced back to much earlier (Miller & Blair, 1985, pp. 1–2). In the Leontief model, flows of products between industry sectors in a specific region are represented in a table based on economic data. In such input-output table, the rows show the transactions of a producer's output to other industries, while the columns present the different inputs necessary to generate a producer's output. Additional final demand tables then provide the sales of a sector's output to final markets (Miller & Blair, 1985).

Such monetary model can be linked to environmental impacts. In environmentally-extended input-output analysis, the upstream or 'embodied' environmental impacts of downstream consumption and goods traded between countries can be determined (Kitzes, 2013, p. 2). Multiregional input-output tables further expanded the geographic coverage following discussions on the environmental impacts embodied in trade and responsibilities thereof (Tukker & Dietzenbacher, 2013, pp. 2–5). Input-output analysis has been applied for timber (e.g. Egenolf et al., 2021; Liang et al., 2016; Zhang et al., 2020) and land (e.g. Fischer et al., 2017; Lugschitz et al., 2011; Weinzettel et al., 2013; Yu et al., 2013) footprints with varying extents of focus on forests.

Ew-MFA has a high product detail and benefits from tracking physical flows which can directly link to impacts such as land use (Henders & Ostwald, 2014). It is thus suitable for analyzing footprints embodied in consumption/trade. However, it is limited for global assessments, by necessary truncation which reduces supply chain coverage, and by the availability of land intensity coefficients (Bruckner et al., 2017; Henders & Ostwald, 2014).

MRIO is particularly powerful in tracking embodied impacts in supply chains, and on a global scale (Henders & Ostwald, 2014). Important limitations include (Bruckner et al., 2015; Henders & Ostwald, 2014; Kitzes, 2013):

- Sectoral aggregation reducing detail and limiting the number of sectors or product categories representing the economy. This causes homogeneity of product outputs and the associated environmental impacts, while intensities (impact per monetary value) can differ strongly within aggregated products.
- The difficulty of accurately assigning environmental impacts such as land use to monetary flows due to this homogeneity and mixing of measured and modelled values.
- Limited regional coverage, requiring aggregation into 'Rest of World' regions.
- Non-marketed (and illegal) commodities and activities are not covered, nor their impacts.
- Differences in data quality per nation, and relatively large time lags in availability can exist.
- Linearity of the model through fixed inputs for each sector.

Both ew-MFA and MRIO can track flows of timber and forestland exchanged between the economy and nature, show the major import/export flows, and are data-intensive. Differences include physical flows (ew-MFA) versus monetary flows (MRIO), and the system boundary limited to a single economy in ew-MFA (e.g. EU as 'black box' in O'Brien & Bringezu, 2018).

Comparing both, the use of physical flows with high product detail is a major strength of ew-MFA, while tracking a product throughout global supply chains without truncation works better in MRIO (Henders & Ostwald, 2014). These strengths of MRIO are weaknesses of ew-MFA, and the other way round. Global footprints would be difficult in ew-MFA with its single economy focus. Yet, even more problematic for ew-MFA is determining driving sectors considering the lack of global supply chain coverage. Input-output analysis is in general better at calculating and analyzing embodied environmental impacts over traditional methods using product coefficients (Kitzes, 2013).

A hybrid method (Fischer et al., 2017) combining physical and economic accounting is also possible. It increases product detail in input-output analysis but is more complex in its set-up with particular assumption and data issues for forestland footprints, and inherits specific disadvantages from both other methods (Bruckner et al., 2017; Fischer et al., 2017).

Although less relevant for forest footprints in this thesis, it is still possible to apply integrated assessment modelling (IAM). This enables analysis of interactions between the socioeconomic system and the environment, including in future pathways. Diaoglou et al. (2019), for example, modelled future biomass supply and demand following scenarios for climate change mitigation. The model can then also determine the land requirements, even specifically enabling to calculate resulting footprints of biodiversity impacts (e.g. Marquardt et al., 2021).

IAMs would enable analyzing the future effects of increasing reliance on the bioeconomy, for example for climate change mitigation. This can be seen as an important advantage. A major downside for determining impacts embodied in trade, is the sectoral aggregation. This is for example seen in the IMAGE model (Stehfest et al., 2014), aggregating sectors of the GTAP database.

2.6. State of literature on timber footprints of consumption

Research to volumetric timber footprints of consumption is limited in number (e.g. Bringezu et al., 2021; Chen et al., 2015; Egenolf et al., 2021; Liang et al., 2016; O'Brien & Bringezu, 2018; Zhang et al., 2020), with reviewed studies presented in Table 1.

O'Brien and Bringezu (2018) applied ew-MFA for the flows of consumed timber products in and out of the EU-27 economy of 2002-2011. FAOSTAT data on roundwood production was used for wood removals, while UN-Comtrade statistics provided data on timber product trade flows.

Chen et al. (2015) applied single-region input-output analysis using official 2007 Chinese input-output tables and (forestry) trade statistics. Other research applied MRIO analysis. Two studies (Bringezu et al., 2021; Egenolf et al., 2021) used the EXIOBASE 3 database, while Zhang et al. (2020) used the EORA MRIO database and Liang et al. (2016) used WIOD 2013. In the case of Zhang et al. (2020) and Liang et al. (2016), the economic tables were extended with FAOSTAT timber harvest data. Such FAOSTAT data as well as World Bank data were used by Egenolf et al. (2021) and Bringezu et al. (2021) to extend EXIOBASE from 2011 to respectively 2015, and 2017 with future projections up to 2030 using future developments data and models.

Existing studies often focus on a single country. Considering Russia's vast forest area and amount of timber exports, Liang et al. (2016) determined which nations are driving Russian timbers harvests. This research stresses the importance of global supply chains. Exports of harvested coniferous and non-coniferous wood were estimated at only 14% and 7% in 2011. Especially domestic wood product sectors consume timber, although to some extent driven by foreign final demand. Russia itself respectively consumed 69.4 Mm^3 (million m^3) and 38.3 Mm^3 of coniferous and non-coniferous Russian timber, equal to 59.6% and 64.9% out of 117 Mm^3 and 59 Mm^3 totals. China, the aggregated 'Rest of World region' and the USA are the top 3 consumers abroad, respectively at 16 Mm^3 (13.7%), 9 Mm^3 (7.7%) and 3.3 Mm^3 (2.8%) for coniferous roundwood, and 3.6 Mm^3 (6.1%), 4.8 Mm^3 (8.1%) and 1.5 Mm^3 (2.5%) for non-coniferous wood.

Other timber footprint studies (Bringezu et al., 2021; Chen et al., 2015; Egenolf et al., 2021; O'Brien & Bringezu, 2018) calculate consumption-based footprints of a specific region. Chen et al. (2015) focused specifically on the use of forest resources within China. Sectors such as 'other construction industries' (293.9 Mm^3), the paper industry (175.4 Mm^3) and construction (144.9 Mm^3) consume the most timber (combined directly and indirectly). An equivalent of 155.2 Mm^3 of timber was imported from elsewhere, which at 40.6% covers a large amount of the required supply. However, details of flows from and to China are limited as the analysis is not multiregional, while the other single-region studies did account for global flows.

Egenolf et al. (2021) determined the timber footprint in the German final consumption to identify sourcing countries and the quantities as well as sustainability of sourced roundwood equivalents. According to this study, 45 Mm^3 or about half of the 9.6 Mm^3 German timber footprint of consumption results from imports. The importance of international trade was further shown by the 38.5 Mm^3 of timber embodied in exports causing a total of 129.1 Mm^3 timber throughput in the German economy. Especially wood from regions such as Africa, Brazil and Southeast Asia was found to be unsustainable. Bringezu et al. (2021) similarly studied the German timber footprint of consumption. The authors found an average of 95.1 Mm^3 roundwood equivalents between 2000 and 2015, falling within 86–114 Mm^3 and 79–118 Mm^3 ranges for the domestic potential of sustainable production in 2015 and 2030. Rising export trends are however considered to put this potential under pressure, demonstrating the effects of global supply chains on sustainable wood consumption.

O'Brien and Bringezu (2018) studied the domestic and worldwide timber footprints of the European Union (EU-27). This research found an increase in EU timber consumption from 463 to 476 Mm^3 between 2002 and 2011, while the production rose from 436 to 480 Mm^3. Imports over this time rose by 9%, particularly by more than 400% for fuelwood.

A focus on global timber footprints is however largely missing, limiting the extent of the results. An exception is Zhang et al. (2020), calculating the global timber harvest footprints of nations, although with a strong focus on selected countries and trade. They found a total direct timber harvest of about 3800 Mm^3 in 2015, growing at a rate of 0.3% per year since 1990. The USA, India and China are the top three harvesting countries with each more than 300 Mm^3, while these countries also have the largest global footprints. The study found the USA to be the largest net importer of embodied timber at 153 Mm^3, followed by Japan at 99 Mm^3 and China at 85 Mm^3.

Aside from the general focus on a region, the above studies all focus on total final consumption, without distinguishing between different consumer groups. Some insights are given by Liang et al. (2016), calculating the share of different final consumers in the total footprints. They found 42.2% and 44.3% household contributions to the global Russian coniferous and non-coniferous roundwood footprints. Second in importance was gross fixed capital formation, with respective values of 40.8% and 38.3% of the footprints. At the same time, Liang et al. (2016) was also the only study providing some information on the global sectors driving timber footprints.

Table 1. Overview of reviewed literature relevant for timber and forestland footprints.

	Aim of the study	**Focus area and timespan**	**Household impacts**	**Method**
Bjelle et al. (2020)	Describing the steps required for a regionally disaggregated MRIO, and comparing the effects on land footprints and embodied land use	Global, 1995-2015	/	MRIO – EXIOBASE 3rx (disaggregated regions)
Bringezu et al. (2021)	Determining key historical and projected global environmental footprints of the German bioeconomy, including volumetric timber footprints	Germany, 2000-2015 + projections 2030	/	MRIO – EXIOBASE 3, using FAOSTAT and World Bank data; other data on future developments for 2030
Bringezu et al. (2012)	Demonstrating an approach to account for the global agricultural and forestland use of nations' consumption, and subsequently assessing these footprints based on the globally acceptable levels of resource use	European Union (agricultural land) & Switzerland (forestland), 2007 + 2030 projections	/	MFA – FAOSTAT, Eurostat, other data; NAI for forestland
Chen et al. (2015)	Examining the forest resource utilization in China using input-output tables	China (mostly internal trade), 2002-2012	/	Single-region input-output analysis – Chinese input-output tables 2007, trade statistics
De Laurentiis et al. (2022)	Building a model to account for the EU's annual land footprint for bio-based products in terms of cropland, grassland and forestland	European Union, 2014-2019, 2018 (reference value)	/	MFA – physical land use model using Eurostat data (trade) and FAOSTAT data, NAI for forestland
Egenolf et al. (2021)	Determining Germany's global volumetric timber footprint, and assessing its self-sufficiency and sustainability	Germany, 1995-2015	/	MRIO – EXIOBASE 3, nowcasts using FAOSTAT and World Bank data
Fischer et al. (2017)	Determining the EU's and Germany's global land footprints of consumption using a new hybrid accounting method combining physical and environmental-economic accounting	European Union and Germany, 1995-2010	/	Hybrid – EXIOBASE 3 with physical LANDFLOW model; for forestland only EXIOBASE
Ivanova et al. (2016)	Determining material, water, land use (aggregated) and greenhouse gas emission footprints of global household consumption	Global, 2007	For all involved footprints	MRIO – EXIOBASE 2
Liang et al. (2016)	Determining global consumption-based volumetric footprints of timber sourced in Russia, and studying its underlying drivers	Global footprints of Russian timber, 1997-2011	Only contribution to total footprint	MRIO – WIOD 2013, FAOSTAT timber harvest data
Lugschitz et al. (2011)	Determining the global land footprints of the EU for satisfying its final demand for agricultural and forestry products	European Union, 1997 & 2004	/	MRIO – GTAP 7 (trade), FAOSTAT (land use), Global Forest Resources Assessment (forestland)
O'Brien and Bringezu (2018)	Building on and further developing the method of global land use accounting to construct volumetric timber and forest area footprints of EU consumption, contributing to the monitoring of global natural resources use	European Union, 2002-2011	/	MFA – FAOSTAT (roundwood removals), UN-Comtrade (trade); NAI for forestland
Weinzettel et al. (2013)	Determining global land and ocean area footprints of consumption, and studying the underlying drivers thereof including the role of affluence, resource endowment and displacement	Global, 2004	/	MRIO – GTAP 7 (trade), FAOSTAT (land use)
Wilting and Vringer (2009)	Analyzing the differences between production- and consumption-based accounting approaches for global land use and carbon footprints	Global, 2001	/	MRIO – GTAP 6 (trade), IMAGE IAM (land use)

Yu et al. (2013)	Determining global land footprints to connect local consumption with global land use, and assess land displacement	Global, 2007	Some attention in shares of products in total land footprints, but not fully clear	MRIO – GTAP 8 (trade), FAOSTAT (land use), Global Forest Resources Assessment (forestland)
Zhang et al. (2020)	Determining global volumetric timber harvest footprints, specifically in selected countries and regarding the role of international trade	Global, 1990-2015	/	MRIO – EORA (version unclear), FAOSTAT for timber harvest data

2.7. State of literature on forestland footprints of consumption

Multiple studies have already been performed in which land footprints were calculated, with varying attention to forestland, but mostly on a global scale (e.g. Bjelle et al., 2020; Bringezu et al., 2012; de Laurentiis et al., 2022; Fischer et al., 2017; Ivanova et al., 2016; Lugschitz et al., 2011; O'Brien & Bringezu, 2018; Weinzettel et al., 2013; Wilting & Vringer, 2009; Yu et al., 2013). Reviewed studies are presented in Table 1.

O'Brien and Bringezu (2018) used ew-MFA to determine the forestland footprint of EU consumption, based on the sustainable yield method using the NAI as described above. Due to limits in MFA methodology, EU and rest of world NAI averages were used based on O'Brien (2016). Bringezu et al. (2012) similarly applied ew-MFA. The authors used data from FAOSTAT and Eurostat among others, and specifically for forestland the NAI to determine required forestland. This was also done by De Laurentiis et al. (2022) through the development of their physical land flow model, but preferring Eurostat data.

The other mentioned studies all applied MRIO analysis. Wilting and Vringer (2009) used GTAP 6, Weinzettel et al. (2013) and Lugschitz et al. (2011) used GTAP 7 and Yu et al. (2013) used the GTAP 8 database. Most of these studies (Lugschitz et al., 2011; Weinzettel et al., 2013; Yu et al., 2013) used FAOSTAT data on land use, while for forestry Lugschitz et al. (2011) and Yu et al. (2013) mention the Global Forest Resources Assessment as data source for productive forestland. Land use data in the study of Wilting and Vringer (2009) was obtained through a combination with the IMAGE Integrated Assessment Model. Multiple studies made use of EXIOBASE. EXIOBASE 2 was used by Ivanova et al. (2016). Fischer et al. (2017) combined EXIOBASE 3 with the LANDFLOW model tracking land flows, but used only EXIOBASE for forestland. The EXIOBASE 3 database was further extended regarding land use by Bjelle et al. (2020) who demonstrated EXIOBASE 3rx with disaggregation into 214 countries.

A specific focus on forestland is generally lacking in literature. Existing studies often aggregate forestland with other biomass land uses such as crops and pasture (Lugschitz et al., 2011) or even built-up area (Wilting & Vringer, 2009) or area for settlements as well as ocean area for fishing (Weinzettel et al., 2013).

Wilting and Vringer (2009) provided early research to worldwide land footprints, distinguishing both production- and consumption-based footprints, indicating the relevance of consumption-based accounting. North America, European OECD countries, the region of 'Japan and New Industrializing Economies' and the Middle East were found to have higher consumption than production impacts on land use, while the opposite was generally the case for developing countries. Such relationship between affluence and land footprints of biomass consumption was studied by Weinzettel et al. (2013). They found the smallest per capita footprints in Bangladesh and Pakistan at 0.4 ha, while the largest were 5.8 ha/capita for Finland and 6.7 ha/capita for Norway. Forestry products were responsible for high footprints in some countries like Finland and Sweden. Twenty-five percent of the footprints embodied in international trade, equal to about 450 Mha, were displaced from high-income to lower-income countries in 2004.

The European Union's agricultural and forestry land embodied in consumption was studied by Lugschitz et al. (2011). The 2004 EU-27 was found to have a total land footprint of about 640.2 Mha, or 1.3 ha per capita with imports and exports respectively representing 374.4 and 36.9 Mha. Finland (4.1 ha per capita), Luxembourg (2.9 ha per capita) and Sweden (2.3 ha per capita) had the largest footprints, while Germany (76.9 Mha) and the United Kingdom (76 Mha) had net trade flows that were the most directed towards imports. Forestry and grazing areas are said to dominate the EU's land footprint, although specific numbers for forestry products are absent.

Ivanova et al. (2016) similarly aggregated the land footprint but focused specifically on household consumption. At 6500 Mha, the study found households are responsible for about 70% of the total land footprint of 2007, with the largest consumers in Australia (16 ha/cap) and Russia (7 ha/cap). Using six aggregated product categories (food, clothing, manufactured products, shelter, services, mobility), food products were found to contribute 46% to household footprints.

Other studies provide limited attention to forestland. Bjelle et al. (2020), for example, calculated the 2015 consumption-based land footprints of 214 countries. The average forestland footprint per capita is 0.365 ha. However, countries like Finland (6.8 ha/capita) and New Caledonia (4.9 ha/capita) strongly exceed this, while Palestine (0.008 ha/capita) and Yemen (0.015 ha/capita) are at the bottom regarding their footprints. This further stresses the large global inequalities.

Yu et al. (2013) gave some forestland estimates in their global land footprint analysis. This study found the particularly large suppliers for the EU in 2007 to be Russia (73 Mha), Africa (32 Mha), Southeast Asia (12 Mha) and China (9 Mha), displacing a total of 149 Mha of forestland. Also, for the USA and China, Russia formed the largest source for embodied forestland, respectively at 22 and 64 Mha.

Fisher et al. (2017) provided calculations on forestland in EU consumption. They found the forestland footprint of Germany to decline from a peak of 41 Mha in 2000 to 29 Mha 2009 and 31 Mha in 2011, driven by footprint reductions in main wood product sectors. For the EU-28, 230 Mha of forestland were required in 2011. The largest share in the EU's imported wood (16%) came from European but non-EU countries, especially Russia. This was followed by Africa (7%), North- and Latin-America (6%) and Asia (5%). De Laurentiis (2022) found the EU's forestland footprint to increase by about 2% per year, at 128.1 Mha in 2018. Out of the 59 Mha imports, 52% was related to wood products, mostly from Russia, while wood pulp originated mainly from Brazil. The EU exported 38.6 Mha, mainly in the form of paper (53%).

A specific focus on forestland, aside of a volumetric timber footprint, is found in the study of O'Brien and Bringezu (2018). The research noted the EU-27 land footprint for forestry products grew from 117 to 122 Mha (0.25 ha/capita) between 2002 and 2011, with a consumption peak right before the 2008 financial crisis. While the EU has a 7% share in global timber harvests, its share in global forest area is 12%. According to O'Brien and Bringezu (2018), the higher timber productivity per hectare within the EU enables the shares of the total forest area and timber harvest to differ. Such differences in productivity were also stressed in the research of Bringezu et al. (2012). They found the 2006 per capita forestland footprint of Switzerland to be at 33% of the globally available per capita forestland, while the use of timber was 105% of the per capita available amount. These results indicate that volumetric forest product footprints and forestland footprints of nations can be very different.

Most of these studies thus did not have a clear focus on studying forestland footprints while often also aggregating different types of land use, with the exception of O'Brien and Bringezu (2018). The attention to driving sectors is similarly limited. Lugschitz et al. (2011) performed a sectoral analysis, but only focused on the UK's land footprint. Yu et al. (2013), had attention for driving sectors, but only regarding the total land footprints. This study seemingly also includes some numbers on the shares of products driving household consumption land footprints in different countries. However, it is unclear to what extent these or other numbers are based on impacts resulting from household final demand. Fisher et al. (2017) mentioned some sectors driving changes in wood demand through time but did not mention numbers nor the current driving sectors for forestland footprints. Some very limited information on main imported and exported products, but aggregated into specific wood products, is provided by De Laurentiis (2022). O'Brien and Bringezu (2018) provided information on the contribution of different product groups in the EU's imports and exports. Aggregated product categories were discussed in Ivanova et al. (2016), but without focus on forests.

2.8. Combining timber and forestland in forest footprints

Volumetric timber footprints can indicate global use of forest resources and displacement of harvests, and is linked to biodiversity impacts. They can provide an indication of sustainability, and can be compared to productivity figures (Egenolf & Bringezu, 2019). Timber footprints also have major implications for climate change. The growing stock volume of forests is often related to the available forest biomass and its carbon stocks, which provide an indicator for the carbon sequestration of forests (FAO, 2020b). Hence, timber harvests provided as volume of wood removals (e.g. FAO, 2020b) can affect the available growing stock volume. This in turn can be linked to changes in biomass, further affecting CO_2 sequestration and carbon stocks.

However, timber footprints do not directly provide an indication of biodiversity impacts. This is particularly the case as for productivity reasons, timber production can have varying forestland requirements as indicated by O'Brien and Bringezu (2018). The loss of forestland through clearance and degradation combined with habitat fragmentation threatens biodiversity globally (Brockerhoff et al., 2017; Purvis et al., 2019; Watson et al., 2018). Similarly to the relevance of using a land indicator for biodiversity impacts from agriculture (Egenolf & Bringezu, 2019), the forestland footprint can be an important indicator for biodiversity pressures. At the same time, crucial forest ecosystem services provided by this biodiversity are also threatened (Brockerhoff et al., 2017). Hence, forestland footprints can also indicate ecosystem services impacts.

Altogether timber and forestland footprints provide complementary information regarding forests. While timber footprints provide indication of harvest volumes, associated sustainability and carbon storage and sequestration, forestland footprints indicate pressures on forests, their biodiversity and ecosystem services.

3. Research method

3.1. Data source

This method applies MRIO analysis for studying global forest footprints, which requires an MRIO database. Multiple MRIO databases exist, including EXIOBASE (Stadler et al., 2018a), EORA (Lenzen et al., 2012, 2013), GTAP (Aguiar et al., 2019) and WIOD (Timmer et al., 2015). Their coverage of time, regions, and sectors and products differs strongly, as seen in Table 2. The EORA database, while covering many countries, aggregates agriculture, forestry and fishery into a single sector (Bjelle et al., 2020). Hence, this database does not fit the purpose of this study. GTAP and WIOD meanwhile have a much lower sectoral resolution than EXIOBASE. Aggregation of sectors and products is often problematic for the accuracy of environmental accounting, such as for embodied land use (Bruckner et al., 2015). A higher resolution thus improves issues of homogeneity (Kitzes, 2013, p. 500). Therefore, EXIOBASE v3.8.3 was chosen for this research.

A downside compared to the GTAP database is the lower country coverage, meaning many countries are aggregated into Rest of World (RoW) regions, missing some country detail of impacts. EXIOBASE 3rx extended EXIOBASE 3 to 214 countries and the timespan to 2015 for land use (Bjelle et al., 2020). However, this data is only available in MATLAB-format and does not allow comparison with timber footprints considering the large difference in number of countries.

Another promising database that is currently being worked on, extending the monetary tables of EXIOBASE, is FABIO (Bruckner et al., 2019). This database disaggregates the agricultural sectors to 127 different products and covers 191 countries from 1986 to 2013. Such sectoral resolution is very useful for analyzing biomass flows in the economy as well as the embodied land required to produce such biomass. The timespan also allows analysis over a long period. Where EXIOBASE only covers a single forest product sector, FABIO covers three. However, studies specifically using FABIO are currently very limited (e.g. Bruckner et al., 2019; Helander et al., 2021). It also does not appear to contain land extensions by itself, Bruckner et al. (2019) for example extended the model for cropland using FAOSTAT data.

EXIOBASE furthermore has the benefit of offering both timber and forestland extensions. Forestland is generally difficult to determine. Statistics on forestland and its productivity are often incomplete, leading to overestimations in studies assuming all reported areas are in use for forestry (Bruckner et al., 2015). Fischer et al. (2017, pp. 17, 33) note how FAOSTAT land use data can be problematic due to varying definitions of forests between countries and difficulties with surveying use of forestland, which is not reported for many countries. Some studies (e.g. de Laurentiis et al., 2022; O'Brien & Bringezu, 2018) use the NAI (annual increment in m^3 per hectare) to estimate the required forestland to grow consumed timber. However, this requires generalizing the NAI for regions with lacking data, and assumes that harvests equate growth, hence also called the 'sustainable yield' method. Difficulties for forestland were noted in the supplements of EXIOBASE 3 (Stadler et al., 2018b), for which a more complex method for determining productive forestland was applied as explained below.

Data on population for per capita footprints and GDP for relating footprints to income levels originate from the DESIRE project which initially led to EXIOBASE 3.

Table 2. Comparison of four often used MRIO databases.

MRIO database	Timespan	Geographic coverage	Sectoral and product coverage
EORA	1990-2015	190 countries	25-500 sectors per country (industries + products)
EXIOBASE	1995-2011, -2015 for energy, -2019 for greenhouse gasses, -2013 for materials	44 countries (EU + major economies), 5 Rest of World regions	163 sectors, 200 products
GTAP	2004, 2007, 2011, 2014	121 countries, 20 Rest of World regions	65 sectors and products
WIOD	2000-2014	43 countries (EU + major economies), Rest of World region	56 sectors and products

3.2. Accessing the database and data processing

Determination of the forest footprints in terms of timber volume and forestland in input-output analysis is performed via matrix calculations. This was done using Python with Pymrio within the Spyder IDE (https://www.spyder-ide.org/) programming environment. EXIOBASE can be downloaded for free (open access) from Zenodo (https://zenodo.org). To access the database, the Pymrio module for Python (Stadler, 2021) will be used. Following the download, EXIOBASE can be accessed using the Pymrio parser (Stadler, 2014):

```
import pymrio

exio3 = pymrio.parse_exiobase3(path = 'exiobase file path')
```

This now enables footprint calculations and analysis to be performed. Some important Python modules providing necessary functions include Pandas (https://pandas.pydata.org/) and Numpy (https://numpy.org/), as well as Matplotlib (https://matplotlib.org/) for visualization.

3.3. MRIO footprint calculation basics

Following Miller and Blair (2009), the basics of the MRIO model can be explained. The total output of the economy $\boldsymbol{x}$ for n sectors and p regions can be represented via a column vector as:

$$\boldsymbol{x} = \boldsymbol{Zi} + \boldsymbol{Yi} \tag{1}$$

In this formula, $\boldsymbol{Z}$ is the matrix of the interindustry sales. It consists of elements z_{ij}^{rs} denoting the sales of sector i in region r to sector j in region s. The matrix $\boldsymbol{Z}$ is multiplied by the summation column vector $\boldsymbol{i}$ to create a column vector with the row sums of the sales of sector i in region r to n sectors of p regions as well as the row sums of the different final demands. Matrix $\boldsymbol{Y}$ is the total final demand, with in each row the sales of sector i in region r to the final demand categories in the covered regions. Multiplication of $\boldsymbol{Y}$ with the summation vector $\boldsymbol{i}$ creates the total final demand vector for all regions $\boldsymbol{y}$.

Technical coefficients a_{ij}^{rs} determine the direct inputs from sector i in region r per unit output of sector s in region j. They are calculated via the following equation:

$$a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_j^s} \tag{2}$$

Which are thus the interindustry sales from sector i in region r to sector j in regions s, divided by x_j^s which is the total output of sector j in region s. Taken together, these elements form the matrix of technical coefficients $\boldsymbol{A}$ of the considered economy. This equation can be rewritten as:

$$z_{ij}^{rs} = a_{ij}^{rs} x_j^s \tag{3}$$

This means that the first equation can be changed to:

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \tag{4}$$

Based on this, the Leontief inverse $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$ can be found by solving (4) for x. $\boldsymbol{L}$ describes both the direct and indirect inputs needed for the various sectors, with $\boldsymbol{I}$ as the identity matrix. This is represented in the following formula:

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} = \boldsymbol{L}\boldsymbol{y} \tag{5}$$

The Leontief inverse is important for the purpose of calculating the total environmental impacts associated with consumption. This is done by introducing a stressor vector $\boldsymbol{e}$ of the direct impacts per unit of output of each sector, which similarly to Brizga et al. (2017) and Wood et al. (2018) leads to (6). Like these studies did, an additional vector with the direct household impacts could be added to the equation. However, this is not relevant for the purpose of the proposed research.

$$\boldsymbol{footprint} = \boldsymbol{e}\boldsymbol{L}\boldsymbol{y} \tag{6}$$

This vector can be produced from a stressor matrix $\boldsymbol{S}$, providing the environmental impacts available in EXIOBASE per unit of output per sector per region. The calculation of this matrix is explained by Stadler (2021, p. 3) and shown in (7). The direct environmental impacts of all sectors in all covered regions are present in the matrix $\boldsymbol{F}$ with the different environmental stressors as rows and the total impacts for each sector in each country per stressor given in the columns. This is divided by the diagonalized total output vector, which is hence denoted by $\boldsymbol{\hat{x}^{-1}}$. As $\boldsymbol{S}$ only provides direct impacts, multiplication with $\boldsymbol{L}$ enables to also include indirect impacts, and further multiplication with $\boldsymbol{y}$ produces the consumption-based footprint.

$$\boldsymbol{S} = \boldsymbol{F}\boldsymbol{\hat{x}^{-1}} \tag{7}$$

3.4. Use of data from EXIOBASE 3

The different matrices that are required, and in particular $\boldsymbol{S}$, $\boldsymbol{L}$ and $\boldsymbol{Y}$, are already present in the EXIOBASE database. From matrix $\boldsymbol{S}$, however, only some stressors are required. The stressors that are of interest for determining forest footprints (timber, forestland) are shown in Table 3. This table also includes other footprints that combine to the total household material (timber + non-timber biomass + mineral) and land (forestland + marginal forestland + agriculture land + other land + infrastructure land), to compare the overall evolution of the forest footprints.

Regarding the material accounts, EXIOBASE contains data for 7 forest products. However, 3 of these, namely natural gums, kapok fruit and raw materials other than wood, will not be used considering the focus is on timber products. The four timber extensions result from FAOSTAT (2015) roundwood removal data (Stadler et al., 2018c).

For forestland, the extensions were determined as explained in EXIOBASE supplements (Stadler et al., 2018b). They result from the intersection of maps on used (Schepaschenko et al., 2015) and intact (Potapov et al., 2017) forests, where mixed grid cells are marginal forestland (for food collection) and intact cells unused. Yet, this implies productive forestland varies in productivity.

Table 3. EXIOBASE 3 stressors used to calculate timber, forestland and global material and land footprints.

	Stressors in EXIOBASE 3	Units in EXIOBASE	Units in this research	Conversion
Timber footprint	Domestic Extraction Used of: • Coniferous wood - Industrial roundwood • Coniferous wood - Wood fuel	kton	m^3; kton (for total material footprint)	1000/0,52 m^3/kton
	Domestic Extraction Used of: • Non-coniferous wood - Industrial roundwood • Non-coniferous wood - Wood fuel	kton	m^3; kton (for total material footprint)	1000/0,68 m^3/kton
Forestland footprint	Forest area – Forestry	km^2	ha	100 ha/km^2
Non-timber biomass footprint	Domestic Extraction Used of: Crop residues, Fishery, Fodder crops, Forestry (Kapok Fruit, Natural Gums, Raw materials other than wood), Grazing, Primary crops	kton	kton	/
Mineral footprint	Domestic Extraction Used of: Fossil Fuels, Metal Ores, Non-Metallic Minerals	kton	kton	/
Agriculture land	Cropland, Permanent pastures, Other land Use (indirect use)	km^2	ha	100 ha/km^2
Marginal forestland	Forest area – Marginal use (activities such as food collection)	km^2	ha	100 ha/km^2
Other land	Other land Use: Total (direct use: subsistence farming, fuelwood collection)	km^2	ha	100 ha/km^2
Infrastructure	Infrastructure land	km^2	ha	100 ha/km^2

To determine the timber footprints, the stressors can be extracted from the matrix $\boldsymbol{S}$ to create the row vectors $\boldsymbol{e_{t,s}}$ and $\boldsymbol{e_f}$ for respectively the relevant stressors s for the timber footprint mentioned in Table 3 and the stressor for forestland. However, these units can be changed to make them more appropriate for calculating per capita footprints and comparison to existing research.

As seen in the literature review, hectares are mostly used for (forest)land footprints. Hence the forestland vector $\boldsymbol{e_f}$ can simply be multiplied by $100\ ha/km^2$. Regarding the timber footprints, the original volumetric values for forestry biomass in EXIOBASE 3 (Stadler et al., 2018a) were converted. This was done using a $0.52\ ton/m^3$ conversion factor for coniferous wood and $0.68\ ton/m^3$ for non-coniferous wood. Considering the data was originally volumetric and volumetric footprints are common in literature, the values of the material timber extensions can also be converted. This is done by multiplying the coniferous stressors by $\frac{1000}{0.52}\ m^3/kton$ and the non-coniferous stressors by $\frac{1000}{0.68}\ m^3/kton$. The four vectors of timber impacts $\boldsymbol{e_{t,s}}$ per wood stressor s can then be summed to the total timber stressor vector $\boldsymbol{e_{t,total}}$.

Similarly, the final demand matrix $\boldsymbol{Y}$ in EXIOBASE consists of multiple categories of final demand. Hence, the final demand of households $\boldsymbol{Y_h}$ should be extracted for the purpose of determining the timber and forestland footprints of household consumption.

3.5. Calculation of the timber and forestland footprints

3.5.1. Determining total footprints per region

After extracting the required household final demand and timber/forestland stressors, the footprints can be calculated. Filling in (6) with the timber and forestland stressors, as well as the household final demand matrix, provides the overall timber and forestland footprints of household consumption summed per region, as shown respectively in (8) and (9).

$$\boldsymbol{TFC} = \boldsymbol{e_{t,total} L Y_h} \quad (8)$$

$$\boldsymbol{FFC} = \boldsymbol{e_f L Y_h} \quad (9)$$

3.5.2. Determining regional footprints with sectoral detail

These total footprints do not provide information on the impact per sectoral demand. It is however possible to determine such sector-specific impacts through diagonalizing the final demand (Miller & Blair, 2009). As the considered system is multi-regional, this will require a slightly different approach following matrix multiplication rules. Household final demand $\boldsymbol{Y_h}$ should be diagonalized per region of demand and per sourcing region. Considering EXIOBASE 3 (49 regions, 200 product sectors), this would mean the diagonalization of each 200 x 1 block (200 rows of demand by region r for each product sector in region s) to 200 x 200. This way, the size of the final demand region expands from 9800 x 49 (rows x columns) to 9800 x 9800. With a diagonalized final demand $\boldsymbol{Y_{h,diag}}$, the equations (8) and (9) become (10) and (11):

$$\boldsymbol{TFC_{sector}} = \boldsymbol{e_{t,total} L Y_{h,diag}} \quad (10)$$

$$\boldsymbol{FFC_{sector}} = \boldsymbol{e_f L Y_{h,diag}} \quad (11)$$

3.5.3. Determining the sourcing regions of the footprints

These calculations still do not provide information on the sourcing regions. As suggested by Wood et al. (2018), such geographical details can be studied by diagonalizing the stressor vector. These diagonalized stressor vectors are then represented as $\boldsymbol{\hat{e}_{t,total}}$ and $\boldsymbol{\hat{e}_f}$. This changes (10) and (11) to respectively (12) and (13). These equations indicate the timber and forestland footprints of the sector-specific final household demand in each region, with impacts distributed over the timber and forestland sourcing regions. If final demand impacts should not be specified by sector, $\boldsymbol{Y_{h,diag}}$ can also be replaced by $\boldsymbol{Y_h}$ to simplify the multiplication.

$$\boldsymbol{TFC_{source}} = \boldsymbol{\hat{e}_{t,total} L Y_{h,diag}} \quad (12)$$

$$\boldsymbol{FFC_{source}} = \boldsymbol{\hat{e}_f L Y_{h,diag}} \quad (13)$$

3.5.4. Aggregating product sectors and regions

Aggregation of sectors or regions is possible through multiplication of above footprints with a concordance matrix. Such matrix has categories (e.g. sectors, regions) to be aggregated as its rows (e.g. 200 products, 49 regions). These rows are connected to the aggregated categories through entering 1 in the corresponding column and 0s for all other columns. Aggregation is achieved by multiplying a resized footprint, e.g. 49x200 for product aggregation or 200x49 for regions with the concordance matrix (e.g. 200x6 products, 49x12 regions).

To get an indication of the type of products, an aggregation into product groups was applied. Product aggregation was similar to existing aggregation in Ivanova et al. (2016) in the categories ‘food’, ‘manufactured products’, ‘shelter’, ‘clothing’, ‘mobility’ and ‘services’. Out of 200 products in EXIOBASE, 170 were found to have household demand and were classified as in Table 4. Regions were furthermore aggregated to enable better analysis of trade flows and to additionally focus on the overall EU footprint (

Table 5). Regional aggregation included the EU27 (2022), major other forest users (the USA, Canada, China, Brazil, India, Russia) and remaining countries in geographic regions (Asia-Pacific, America, Middle East, Europe, Africa).

Table 4. Product groups contained in the aggregated product categories used in this research. N = number of products included in each category.

Product category	Included products
Shelter	Electricity, fuels, materials required for shelter, waste treatment, services for construction, real estate, electricity (N = 86)
Food	Processed and unprocessed food items, fertilizers (N = 28)
Clothing	Textiles, leather, furs, wool, plant fibers (N = 5)
Mobility	Motor vehicles, maintenance thereof, other transport equipment, engine fuels, transportation services (N = 19)
Manufactured products	Paper, plastic, rubber, metal manufactured products, furniture and other manufactured products, machinery, electronic devices, precious metals, secondary raw materials (N = 14)
Services	Hotel, retail, financial, health, educational, recreational, etc. services without those classified under shelter and mobility (N = 18)

Table 5. Regions included in each aggregated region used in this research. RoW = Rest of World.

Aggregated region	Included EXIOBASE regions
Brazil	Brazil
Canada	Canada
China	China
India	India
Russia	Russia
USA	USA
Africa	RoW Africa, South-Africa
America	RoW America, Mexico
Asia-Pacific	RoW Asia-Pacific, Australia, Indonesia, Japan, South-Korea, Taiwan
EU27 (2022)	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
Europe	RoW Europe, Norway, Switzerland, Turkey, UK
Middle East	RoW Middle East

3.6. Calculating trade flows of embodied timber and forestland

3.6.1. Determining imports and exports in regions' forest footprints

Using the outcome of previous equations, the footprints embodied in imports and exports can be determined. This is for example done in Brizga et al. (2017). The authors calculate the imports of region r by setting the final demand of regions other than r to zero and setting the stressor vector for region r to zero. Exports are then calculated by setting both the final demand of region r as well as the stressor vector for regions other than r to zero. However, the outcomes of (12) and (13) can also be used for this. The imports and exports are then analyzed through element-wise multiplication with a matrix $\boldsymbol{G}$, containing zeros for all domestic impacts and ones for all other elements. Hence, all impacts by region r in region r are set to zero, leading to (14) and (15) for respectively volumetric timber footprints and forestland footprints. These equations keep the sectoral detail of the footprints as produced by $\boldsymbol{Y_{h,diag}}$.

$$\boldsymbol{TFC_{trade}} = \boldsymbol{\hat{e}_{t,total} L Y_{h,diag} G} \quad (14)$$

$$\boldsymbol{FFC_{trade}} = \boldsymbol{\hat{e}_{f} L Y_{h,diag} G} \quad (15)$$

For each region r, the footprints embodied in international trade can then be determined. The imports of timber and forestland for region r, $\boldsymbol{Im_{timber,r}}$ and $\boldsymbol{Im_{forestland,r}}$ are produced by extracting the sum of all rows for the final demand region r and subsequently summing impacts per product sector in region r. The exports, $\boldsymbol{Ex_{timber,r}}$ and $\boldsymbol{Ex_{forestland,r}}$ result from summing all columns containing the impacts exported to final demand regions for sourcing region r.

3.6.2. Determining the trade balance of forest footprints

The trade balance for embodied timber and forestland (e.g. as in Zhang et al., 2020) for region r is then calculated as in (16) and (17). A negative value means a region is a net importer. The trade balance works as an indicator for displaced environmental pressure through international trade, as considered by Wood (2018).

$$\boldsymbol{TB_{timber,r} = Ex_{timber,r} - Im_{timber,r}} \quad (16)$$

$$\boldsymbol{TB_{forestland,r} = Ex_{forestland,r} - Im_{forestland,r}} \quad (17)$$

4. Results

4.1. Forest footprints at the global scale

4.1.1. Role of households in total timber and forestland footprints

As indicated by Table 6, household consumption drives most of the forest footprints. While household demand is responsible for 54% of the timber footprints (total 3966 Mm^3 in 2011), the requirements in terms of forestland are even higher at 60% of the total (2214 Mha in 2011). The second largest contributor is gross capital formation at respectively 35% and 30%, required to produce goods. Other categories, however, have minor contributions to the forest footprints.

Table 6. Shares of EXIOBASE consumption categories in the total timber and forestland footprints of 2011. NPISH = Non-profit institutions serving households. Gross capital formation is about fixed assets, which are goods or services used for production (United Nations et al., 2009, pp. 198–199). Changes in inventories result from price changes of goods held in storage (United Nations et al., 2009, pp. 207–208).

	Households	NPISH	Governments	Gross capital formation	Changes in inventories
Timber footprint	54%	2%	5%	35%	3%
Forestland footprint	60%	2%	5%	30%	3%

4.1.2. Timber in the global material footprint of household consumption

The world's total material footprint of household consumption (Figure 1) grew steadily over time. Between 1995 and 2011, the material footprint increased by about 34% from 23.3 Gt to 31.3 Gt. However, the period of the financial crisis is marked by a plateau and small decrease between 2008 and 2010.

The largest contribution to the growing material footprint occurred in the mineral-based fraction, increasing by 47% from 10.6 Gt to 15.6 Gt. The total biomass footprint meanwhile grew from 12.7 Gt to 15.7 Gt (+24%). Yet, the timber footprint remained mostly steady, decreasing slightly from 1.41 Gt in 1995 to 1.36 Gt in 2011 (-4%).

The larger relative growth of mineral resource consumption is also visible in the changing shares in the global material footprint presented in Figure 1. In 2011, both the biomass and mineral-based resources represented 50% of the material footprint. The share of biomass in the material footprint decreased from 54% in 1995, despite growing biomass consumption. As the timber footprint of household consumption remained stable, its share in the material footprint decreased from 6% to 4% between 1995 and 2011.

A closer look at the total global biomass footprint of household consumption (Figure 2) stresses the growing contribution of non-timber biomass. This results in a relatively small share of timber in the biomass footprint, decreasing from 11% to 9% between 1995 and 2011. The growth of the biomass footprint continued very steadily until the 2008 financial crisis. Although the plateau and decline seen in this period is similar to the mineral-based footprint, the resumed growth since 2010 is relatively limited.

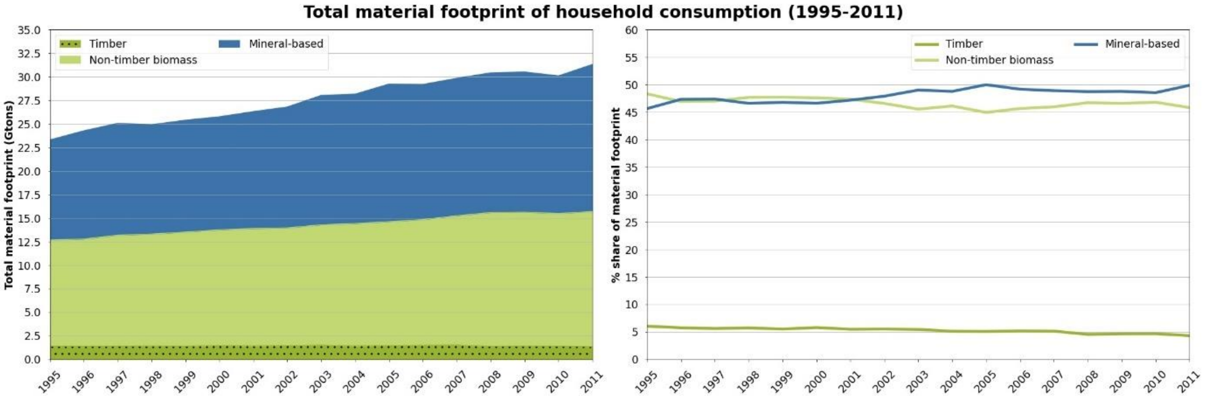

Figure 1. (a) Global mineral, non-timber biomass and timber footprints of household consumption (gigatons) over the period 1995-2011. (b) Shares of mineral , non-timber biomass and timber fractions in the global material footprint over the period 1995-2011.

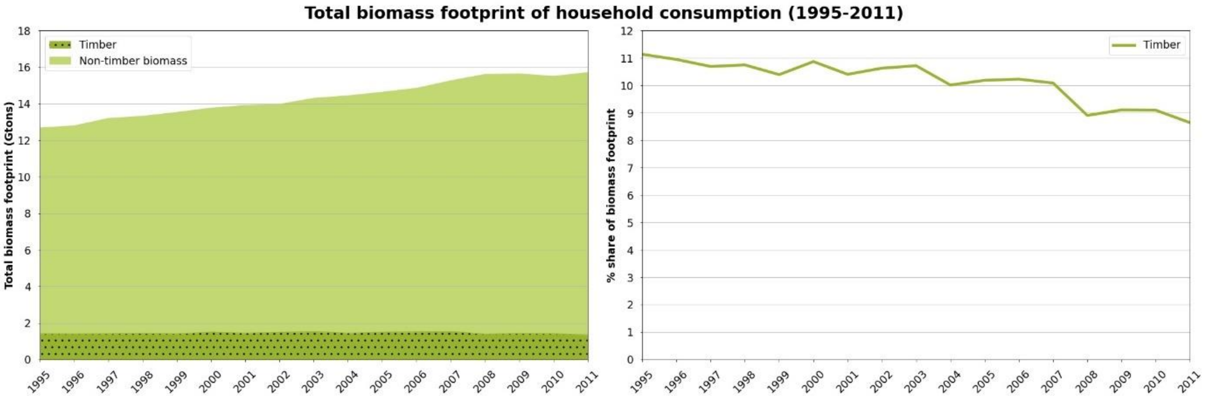

Figure 2. (a) Global non-timber biomass and timber footprints of household consumption (gigatons) over the period 1995-2011. (b) Share of timber in the global biomass footprint over the period 1995-2011.

Figure 3 (or Appendix Figure A-1) shows major differences across regions' shares of biomass in the material footprint and shares of timber in the biomass footprint of 2011. The shares of biomass in the material footprints range between 20% (Malta) and 80% (Brazil). The contributions of timber to this biomass footprint are overall much lower, but still vary widely between 3% (Netherlands) and 23% (Finland).

Both shares differ strongly in countries such as Indonesia (78% biomass in material footprint, 4% timber in the biomass footprint), Brazil (resp. 80% and 7%) and India (resp. 71% and 5%). This indicates a high share of biomass in the material footprint does not equate to a large contribution of timber in the biomass footprint. A clear exception exists in the case of Rest of World (RoW) Africa, with shares of respectively 75% and 17%.

Linking these shares to income reveals a quadrant pattern (Figure 3). Low- to middle-income countries have the largest shares of biomass in their material footprints. This is seen in regions such as Brazil, Indonesia, India, Mexico, RoW Americas, RoW Europe, Russia, South-Africa, Romania and RoW Asia-Pacific having the highest shares of biomass in their material footprints (> 50%). While a large non-timber bioeconomy is mostly seen in emerging countries, RoW Africa's important bioeconomy depends relatively more on timber.

Meanwhile, some of the largest shares of timber in the biomass footprints are found in higher income countries with lower overall dependency on biomass. This is particularly evident because of Finland and Sweden having the largest shares of timber in their biomass footprints, and Austria completing the top 5 alongside Slovenia and Russia. Yet, unlike the biomass in material footprint shares, this trend does not extend past the countries with the highest shares of timber in their biomass consumption.

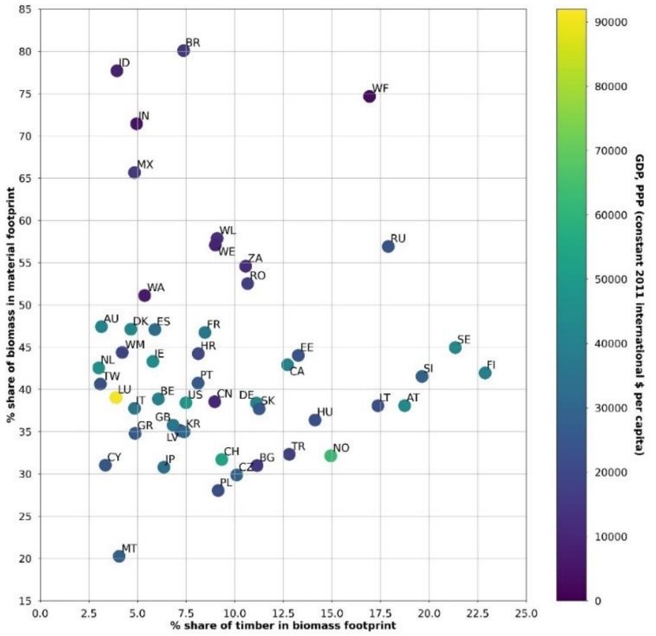

Figure 3. Regional shares of biomass in material footprints versus regional shares of timber in biomass footprints in 2011, in relation to the income level (GDP PPP constant 2011 international $ per capita).

4.1.3. Global volumetric timber footprint

The global volumetric timber footprint provides better insight into households' timber consumption. All figures in this section express volumetric timber footprints in order to compare to existing literature and better represent the original volumetric data from the FAO. To do so, the EXIOBASE wood extraction stressors are converted from kton to m^3 using the initial conversion factors for coniferous and non-coniferous wood (see methods).

The volumetric timber footprint hiked steeply since 1995 and peaked in 2007, followed by a declining trend and a 4% lower footprint in 2011. The decline has been driven by the decrease in fuelwood, however the mitigation has been largely offset by the increase in industrial roundwood.

Figure 4 shows the evolution of the total global volumetric timber footprint of household consumption and its components. In volumetric terms, the timber footprint decreased from 2242 Mm^3 in 1995 to 2158 Mm^3 in 2011. The shares of fuelwood and industrial roundwood in 2011 are similar, respectively at 1124 Mm^3 and 1034 Mm^3. This is very different from 1995 when the fuelwood footprint was at 1365 Mm^3 and industrial roundwood at 877 Mm^3. As a result, the share of fuelwood in the total timber footprint of household consumption decreased from 61% to 52%, while industrial roundwood increased from 39% to 48%.

The global fuelwood footprint remained mostly stable until a decline started in 2008. Meanwhile, the total industrial roundwood footprint increased over most of the timeline, except for 1998 and 1999 when it temporarily declined. Ultimately, the fuelwood footprint decreased by 18% relative to 1995, while the industrial roundwood footprint increased by 18%.

Contributions of coniferous and non-coniferous wood types changed over time, as seen in Figure 4 and Figure 5. Most of the increase in industrial roundwood has been supplied by a continuous increase in non-coniferous wood. Industrial roundwood of non-coniferous origins increased by 35%, from 343 Mm^3 to 462 Mm^3 in 2011. Coniferous industrial roundwood accounted for 572 Mm^3 in 2011 compared to 534 Mm^3 in 1995, providing a smaller increase of 7%. Interestingly, coniferous fuelwood decreased by 29% from 180 Mm^3 to 127 Mm^3, while non-coniferous fuelwood decreased by 16% from 1185 Mm^3 to 997 Mm^3. Hence, coniferous roundwood contributed less to the increase of the industrial roundwood footprint and relatively more to the decrease of fuelwood. This could indicate a shift towards more non-coniferous wood types.

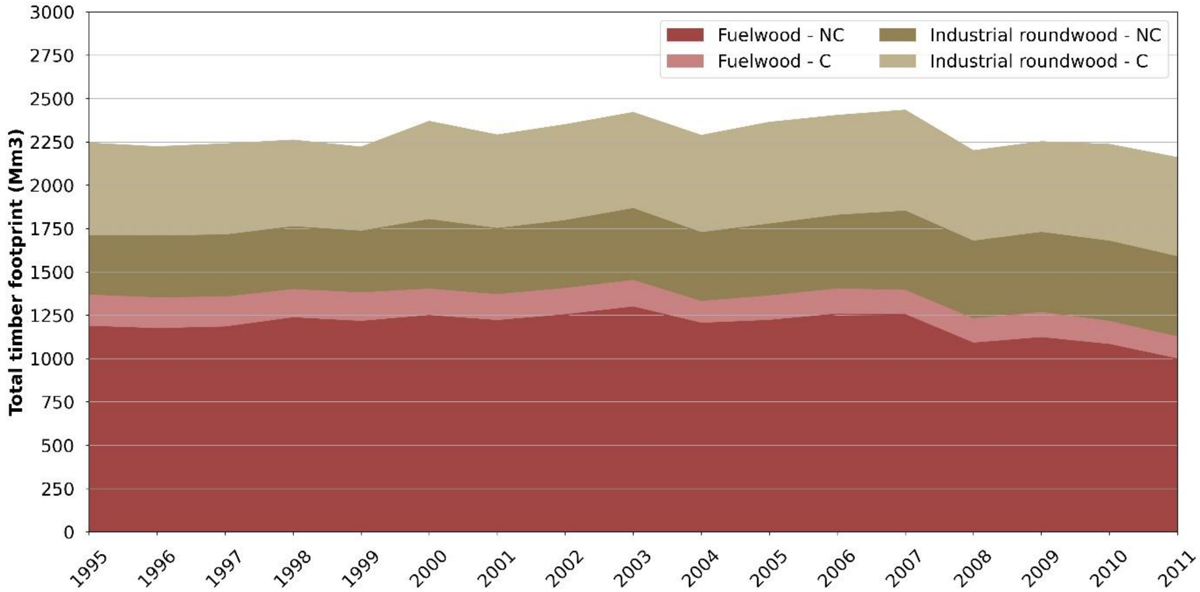

Figure 4. Evolution of the timber footprint of global household consumption (million m^3) over the period 1995-2011 and contributions of different timber categories. C = coniferous, NC = non-coniferous.

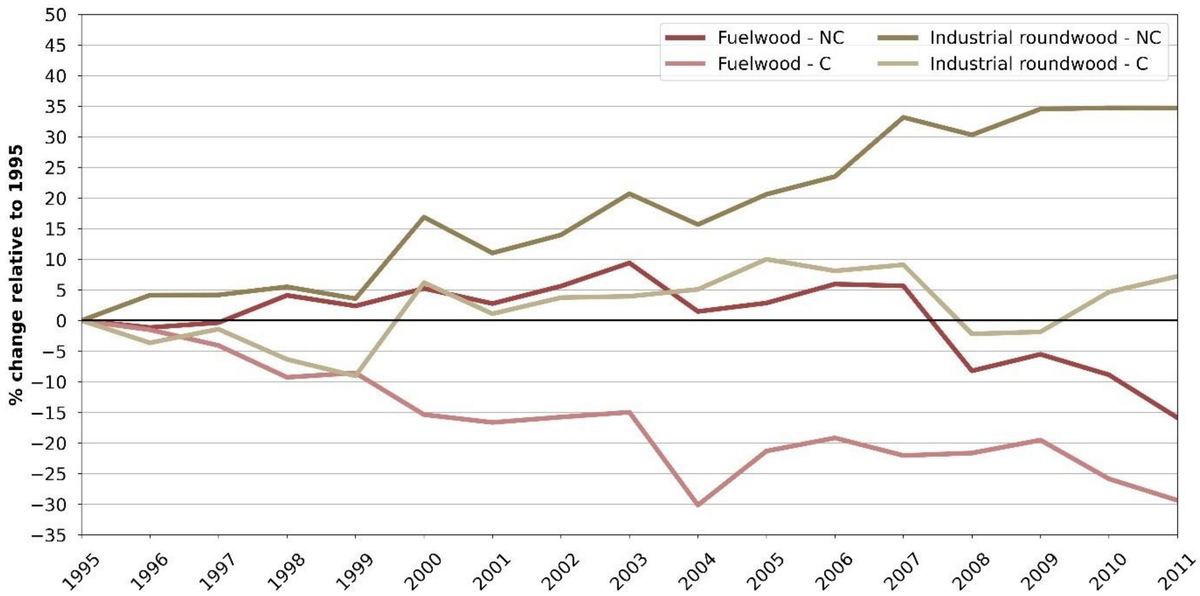

Figure 5. Percentage change of each timber category in the total timber footprint of global household consumption relative to 1995. C = coniferous, NC = non-coniferous.

The decrease in fuelwood has relieved timber consumption since 1996, but the net effect is minimal, as this decrease is undermined by the increase driven by industrial roundwood. Figure 5 shows that fuelwood (non-coniferous and coniferous) declined by 2011 with respect to baseline year 1995. On the contrary, industrial roundwood of both kinds grew, with larger growth of non-coniferous wood (+35% versus +7%). Coniferous fuelwood decreased more (-29%) than non-coniferous fuelwood (-16%) by 2011, with the latter only starting to decline after 2007. Overall, coniferous wood in the timber footprint decreased from 714 Mm^3 to 700 Mm^3 (-2%), while non-coniferous wood decreased from 1528 Mm^3 to 1459 Mm^3 (-5%). Both decreases are due to the lower consumption of fuelwood.

As seen in Figure 6, large differences exist in regions' contributions to the global timber footprint of household consumption. The four largest consumers, RoW Africa (443.3 Mm^3), China (239.2 Mm^3), USA (217.5 Mm^3) and Brazil (173.5 Mm^3) are together responsible for 50% of the global timber footprint. The 31 smallest consumers out of a total of 49 regions represent only 10% of this footprint. RoW Africa (+22%), the USA (+30%) and Brazil (+60) are furthermore still increasing their footprints. China's footprint decreased (-28%), and India (-64%) is particularly notable as it is no longer a top five consumer.

RoW Africa alone contributes to 21% of the timber footprint, with its households contributing to 36% (at 402.2 Mm^3) of the global household fuelwood footprint. Major fuelwood footprints are mostly found for emerging economies: China (130.4 Mm^3), India (79.6 Mm^3), South America (78.6 Mm^3) and Brazil (77.8 Mm^3).

The USA is the largest consumer of industrial roundwood at 169.1 Mm^3, equal to 16% of the global household industrial roundwood footprint. Other large industrial roundwood consumers include the emerging economies Russia (141.6 Mm^3), China (108.8 Mm^3) and Brazil (95.7 Mm^3). The EU also consumes a lot of industrial roundwood (166.6 Mm^3), and its households could be considered the second largest timber consumers on a global scale (251.6 Mm^3), although this is a 14% reduction.

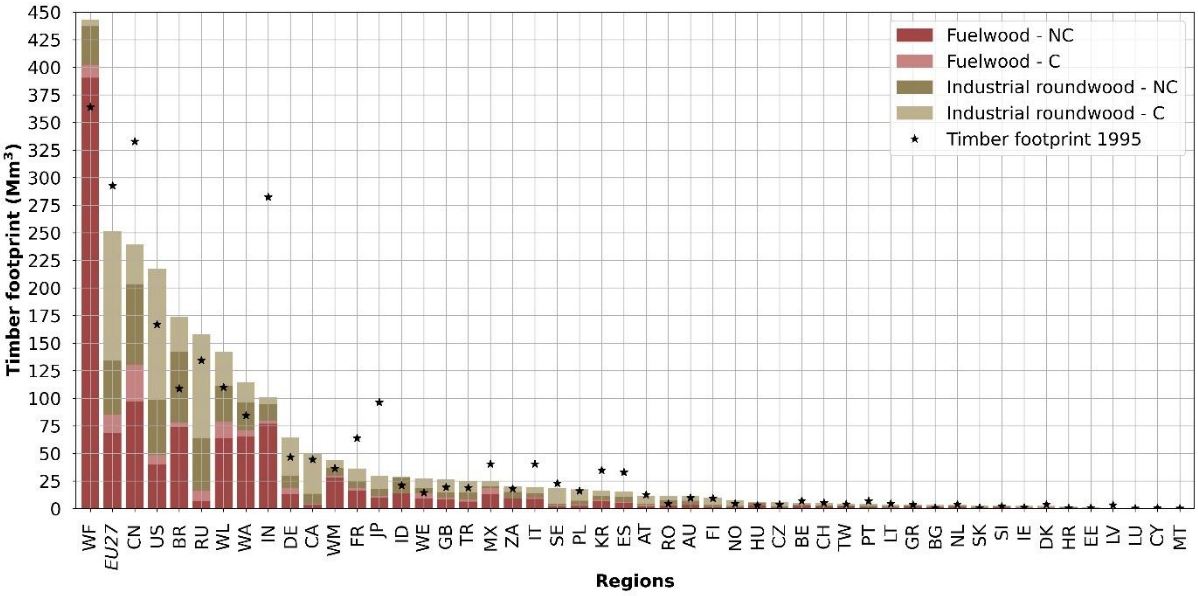

Figure 6. Regional timber footprints of household consumption (million m³) in 2011 versus 1995. C = coniferous, NC = non-coniferous.

4.1.4. Trade of timber embodied in household consumption

4.1.4.1. Imports and exports of embodied timber

The timber present in regions' household consumption is sourced both domestically and abroad, with major differences between regions. Most nations increased their trade flows of embodied timber, imports and exports, reflecting the increased role of trade and globalization since 1995. Out of 49 regions in this study, 38 regions increased their imports, and 38 increased their exports relative to 1995.

Volumes of timber in trade show the regions displacing the most timber harvests (Figure 7, Appendix Figure A-2). The largest importer is China (98.7 Mm^3), followed by the USA (73 Mm^3) and India (42.4 Mm^3). China's imported timber footprint is more than double the footprint of the third largest importer, India. Moreover, all three strongly increased their imports. China grew its imports by 352% from 21.9 Mm^3 in 1995. The USA doubled its imports (+101%), up from 36.3 Mm^3 in 1995. Particularly India also forms an interesting case, becoming a large importer by increasing its imports by 4787% from only 0.9 Mm^3 in 1995.

The top 5 imports of embodied timber is completed by RoW Asia-Pacific (39.3 Mm^3) and Germany (32 Mm^3). Germany has also seen a large increase in imports of embodied timber (+43%), while other major increases occurred in RoW Middle East (+51%), RoW America (+143%) and the UK (+44%). The EU is also a major importer at 67.1 Mm^3, but decreased its imports by 44% relative to 1995, likely as a result of intensifying internal trade considering the EU's household footprint only slightly decreased.

Multiple nations decreased their imports. In 1995, Japan was the largest importer of embodied timber (90 Mm^3) dropping down to 22.8 Mm^3 (-74%) in 2011. France (-58%), Italy (-55%), South-Korea (-61%) and Spain (-61%) all imported much less embodied timber in 2011. However, in most regions (38 out of 49), the imports increased.

The major global exporters for timber embodied in household consumption are provided in Figure 7 and Appendix Figure A-3. Particularly large exporters include RoW Asia-Pacific (111 Mm^3), RoW Africa (90.2 Mm^3), China (62 Mm^3) and the USA (43.6 Mm^3). RoW Asia-Pacific exports 19.7% of all embodied timber. Malta is the only region without exports driven by foreign household consumption.

The strongest increases in exports compared to 1995 occurred in China, up from 13.4 Mm^3 (+362%), Russia up from 0.5 Mm^3 to 29.2 Mm^3 (+5824%) and RoW Asia-Pacific up from 84 Mm^3 (+32%) in 1995. Similar to the timber imports, 38 out of 49 regions increased their exports. Interestingly, the EU increased its exports by 73% to 42.8 Mm^3, becoming a prominent region for timber production to satisfy international consumption.

A notably large decrease in exports occurred in Indonesia, down from 41 Mm^3 in 1995 to 5.3 Mm^3 in 2011 (-87%), although its own footprint slightly increased. Other decreases include RoW Africa down from 103.2 Mm^3 (-13%), the USA down from 65 Mm^3 (-33%) and Canada decreasing from 45.5 Mm^3 in 1995 to 30.8 Mm^3 in 2011 (-32%).

4.1.4.2. Trade balance of embodied timber

The overall net trade balance (Figure 7, Appendix Figure A-4) indicates the trade balance is related to both differences in income and forest abundancy, with an overall mixed picture.

Among the top 5 of net-importers are China (-36.8 Mm^3), RoW Middle East (-29.9 Mm^3), the USA (-29.5 Mm^3), Germany (-24.3 Mm^3) and Japan (-23.4 Mm^3). Japan, despite much reduced imports remains an important net importer, although its trade balance was -89.9 Mm^3 in 1995. The USA (+28.7 Mm^3 in 1995) and India (+15 Mm^3 in 1995 versus -16.3 Mm^3 in 2011) show clear changes from net exporter to net importer of timber for household consumption. This group overall consists of a mixed bag of large emerging economies (India, China) and wealthy industrial economies (Japan, USA, Germany, etc.), while RoW Middle East has limited forest resources. The EU is a relatively large net importer (-24.4 Mm^3), although this is a 75% reduction relative to 1995 due to large export increases and import decreases.

Also notable is the much more negative trade balance of China, which was at -8.5 Mm^3 in 1995, and almost -36.8 Mm^3 in 2011 due to stronger growth of imports compared to exports. Strong decreases in Italy, South-Korea, France and Spain can be related to their overall decreased imports.

The differences between top net exporters are much larger. Particularly notable are RoW Africa (+78 Mm^3) and RoW Asia-Pacific (+71.1 Mm^3), which are followed at a distance by Russia (+20.3 Mm^3), Canada (+19.3 Mm^3) and Brazil (+16.1 Mm^3). Overall, the group of top net exporters is mixed with some of the wealthiest regions that are abundant in forests (Sweden, Canada, Finland) together with low- and middle-income regions (RoW Africa and Asia-Pacific, and Russia, Brazil).

Even though RoW Africa is the largest net exporter, it has decreased from 99.1 Mm^3 in 1995, due to the combination of more imports and reduced exports. Particularly Indonesia (+39.2 Mm^3 in 1995 versus 1.9 Mm^3 in 2011), but also Canada (+35.6 Mm^3 in 1995 versus +19.3 Mm^3) have become less prominent net exporters due to export reductions. Russia on the other hand switched from being a net importer to net exporter as its exports grew strongly over time. Similarly, RoW Asia-Pacific became a much larger net exporter, up from 42.9 Mm^3 in 1995.

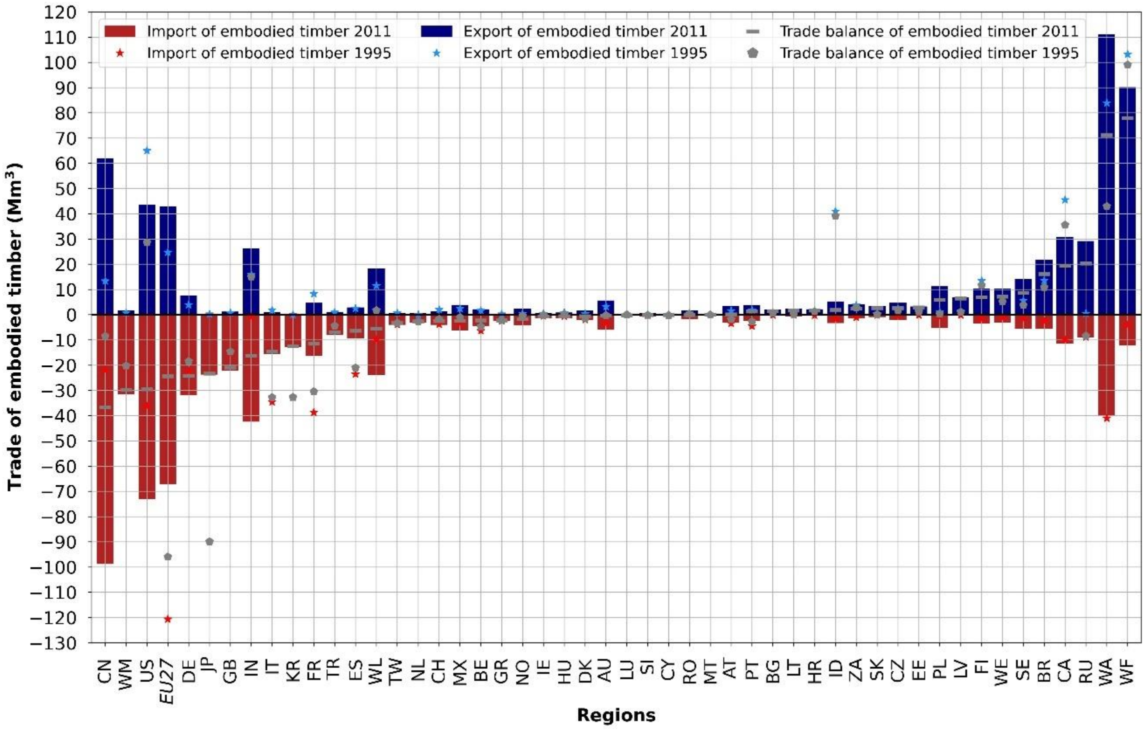

Figure 7. Imports, exports and trade balance of embodied timber (million m^3) to satisfy household consumption in 2011 compared to 1995. Regions sorted from net importers (left) to net exporters (right).

4.1.4.3. Displacement of household timber footprints

On average, countries displaced 48% of their household timber footprints in 2011, increasing from 38% in 1995. Most regions (35 out of 49) also increased the share of displacement in their household timber footprints (Appendix Figure A-9). In general, the dependency on displacements is larger in high-income countries, emerging economies (e.g. Taiwan, India, China) and countries with limited resources (e.g. RoW Middle East) (Appendix Figure A-8).

Four countries displaced more than 99% of their footprints in 2011: Malta, Luxembourg, Cyprus and the Netherlands. These are notably all EU countries with few forest resources of their own. However, large dependency on displacements in high-income countries is seemingly less related to resource availability, as seen in Switzerland (81%) or Norway (55%). This is in contrast with Brazil (3%) and Russia (6%) with a lot of resources but lower incomes. The lowest displacements (under 10%) are furthermore found in RoW Africa (3%) and South-Africa (8%).

Overall, twenty-one regions (13 of which within the EU) displace at least 50% of their timber footprint. Yet, the EU depended for only 27% of its footprint on displacements in 2011, a decrease of 15%. This is likely driven by a combination of increased internal trade and large decreases in Italy (-80%), Spain (-60%), and France (-45%).

4.1.4.4. Bi-lateral trade flows of embodied timber

Major global trade flows of timber exist, as detailed in Figure 8. Five regions (aggregated as in Table 5) produce 65% of the global timber for household consumption. Africa (RoW Africa + South-Africa) alone produces 25% of the global timber, followed by Asia-Pacific (RoW Asia-Pacific, Australia, Indonesia, South-Korea and Japan) with 11%, EU27 (11%), China (9%) and Brazil (9%). Meanwhile, five regions consume 64% of the global timber. This is also led by Africa with 21%, and followed by the EU27 (12%), China (11%), the USA (10%) and Asia-Pacific (9%). Proximity between regions seems to play a role in determining the volume of the bi-lateral flows, but does not solely explain it.

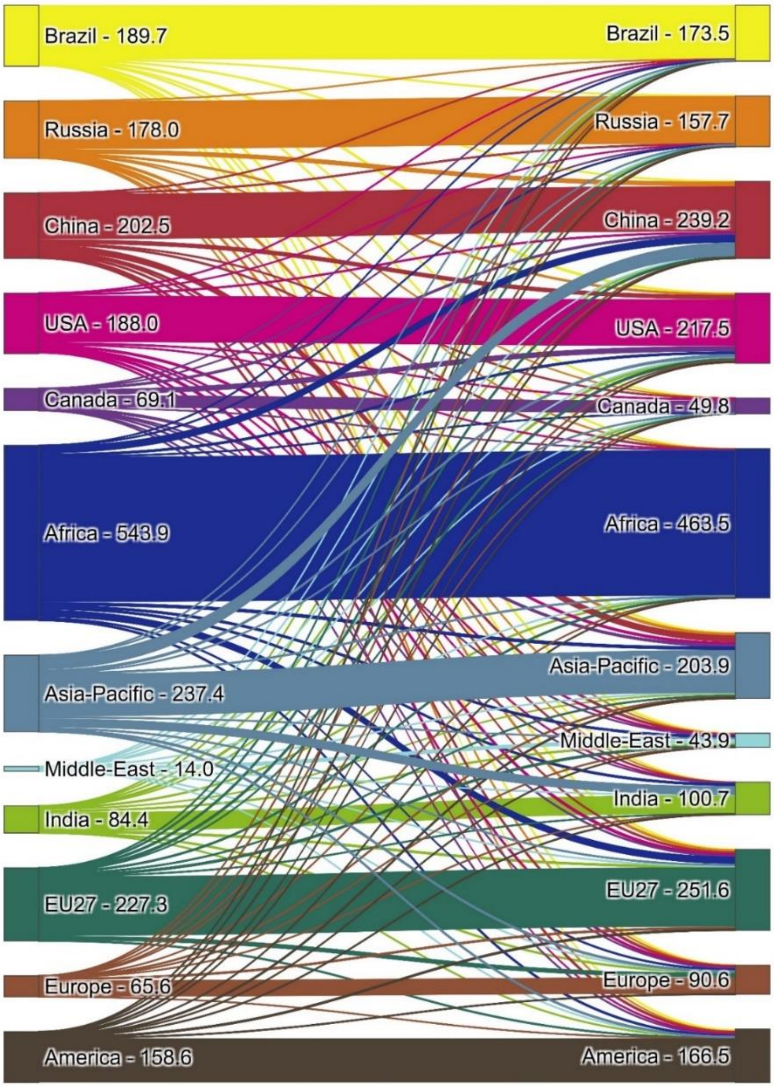

Figure 8. Trade flows between major sourcing regions (left) and major consumers (right) of embodied timber (million m^3) in 2011. Regions aggregated as in Table 5

China was the largest importer in 2011 (98.7 Mm^3), and displaced 41.3% of its timber footprint, mostly to regions such as Asia-Pacific (42.7 Mm^3), Africa (23.5 Mm^3) and Russia (14.4 Mm^3), as shown in Figure 8. This indicates high dependency on a limited number of sourcing regions.

The USA is the second largest importer (73.1 Mm^3, 34% of its footprint), with imports spread over different regions. The largest amounts are sourced from Canada (17.2 Mm^3) and China

(13.8 Mm^3). The Asia-Pacific region is the third largest importer of timber embodied in household consumption (70.6 Mm^3). About half is sourced from China (20.7 Mm^3) and Africa (11.2 Mm^3), while the USA (9.5 Mm^3) is also a major sourcing country.

The total displacement of timber in the EU27 almost halved from 120.7 Mm^3 in 1995 to 67.1 Mm^3 (-44%) in 2011 (see Figure 8 and Appendix Figure A-11). This is in stark contrast with the other regions increasing their displacement, except for Asia-Pacific (-18%). The EU sources from multiple regions, with the largest imports coming from Africa at 22.9 Mm^3, followed by China (8.6 Mm^3) and non-EU Europe (8 Mm^3).

The EU has seen major changes relative to 1995. Displacement to Africa reduced strongly from 72.4 Mm^3 to 22.9 Mm^3. Large reductions are also seen from the USA (17.2 Mm^3 to 5.3 Mm^3) and Canada (10.3 Mm^3 to 1.5 Mm^3). Displacement to Brazil and other American countries declined slightly. Yet, major increases are seen in displacement to China (0.9 Mm^3 in 1995) and non-EU Europe (up from 2.8 Mm^3).

India meanwhile imported 42.5 Mm^3 of embodied timber, particularly from other Asia-Pacific countries (28 Mm^3) and Africa (9 Mm^3). Non-EU Europe countries together import 39.3 Mm^3, with more than half coming from the EU (14.4 Mm^3) and Africa (7.4 Mm^3). The America region imported 29.1 Mm^3, with half of this amount coming from the same continent: 7.3 Mm^3 from the USA and 7.2 Mm^3 from Brazil. The least amount of timber is imported by the regions Africa (12 Mm^3), Russia (8.9 Mm^3) and Brazil (5.6 Mm^3). Canada also has limited imports at 11.5 Mm^3, with most (6.5 Mm^3) coming from the nearby USA. Still notable is the Middle East region, which imports a large amount of the timber for its household consumption at 31.6 Mm^3

4.1.5. Global land and forestland footprints of household consumption

The total global land footprint of household consumption was fairly stable in the period 1995-2011, decreasing slightly (-3%) from 8545 Mha to 8315 Mha (Figure 9). Indirect land (forestland and agriculture) represented 55% of the total land footprint of household consumption in 2011, compared to 45% for direct land (marginal forestland, infrastructure and 'other land').

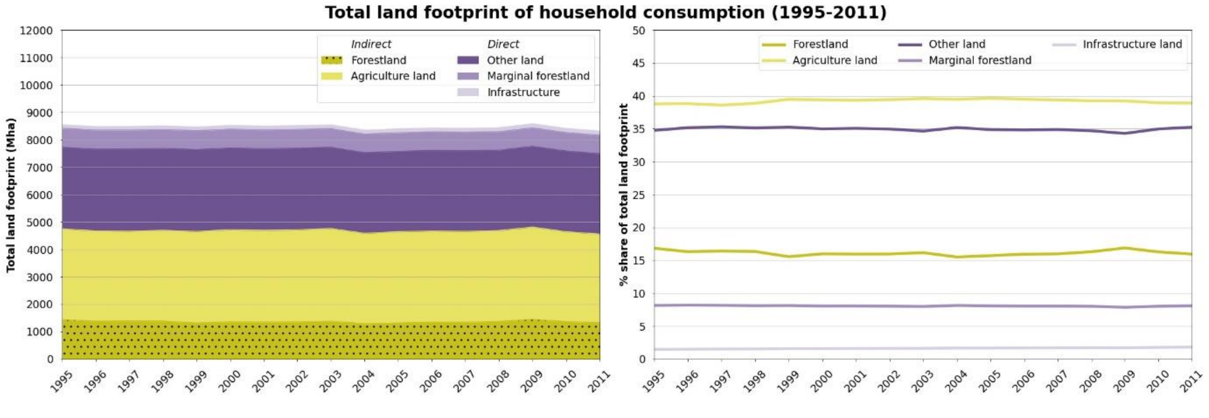

Figure 9. (a) Global direct and indirect land footprints of household consumption (million hectares) over the period 1995-2011. (b) Shares of land footprints in the total land footprint of household consumption over the period 1995-2011.

The indirect land footprint of households also remained fairly stable between 1995 and 2011 (Figure 9), changing slightly from 4751 Mha to 4561 Mha (-4%). No strong drops or increases are visible over this period. Particularly forestland contributed to the decline in the indirect land footprint, as it decreased from 1439 Mha in 1995 to 1327 Mha in 2011 (-8%). Land for agriculture decreased from 3313 Mha to 3234 Mha (-2%) over this period. However, despite these decreases, the forestland and agriculture land footprint remain important in the total land footprint, with shares respectively reducing from 17% to 16% and remaining stable at 39%.

Figure 9 further indicates household consumption causes a major direct land footprint, which remained very stable as it changed from 3793 Mha in 1995 to 3754 Mha in 2011 (-1%). This was generally driven by changes in ‘other land’ and marginal forestland. Most of the direct land footprint is ‘other land’, which decreased slightly from 2970 Mha to 2929 Mha (-1%) over the period 1995-2011. The marginal forestland footprint also declined, from 697 Mha to 674 Mha (-3%). Land categorized as ‘other land’ is likely linked to subsistence farming and includes direct fuelwood harvests. Marginal forestland in EXIOBASE is considered to not include timber harvests, but instead other activities such as food collection. Contrary to these trends, land for infrastructure increased by 19% from 127 Mha to 151 Mha. Yet, contributions to the total land footprint remained stable for ‘other land’, marginal forestland and infrastructure, respectively at 35%, 8% and 2%.

4.1.6. Global forestland footprint

Zooming in on the global forestland footprint (Figure 10), the gradual decline over time to 1327 Mha in 2011 is visible. Although the relative change appears as rather volatile, a decrease is seen throughout the 1995 to 2011 period, except for 2009.

When comparing the forestland footprint (Figure 10) to the timber footprint (Figure 4), drops in 1996, 1999 and 2004 occur in both cases. However, the period around the 2008 financial crisis offers an interesting picture. While the timber footprint peaks in 2007 and subsequently declines to a lower plateau between 2008 and 2011, the forestland footprint can be seen peaking instead of falling.

When considering relative changes in forestland footprints, about half of the regions in this study (25 out of 49) decreased their forestland footprint (Figure 11). Yet, the absolute changes in Russia’s forestland footprint appear to be the main reason for the declining global forestland footprint of household consumption. The differences are also large compared to the global timber footprint (Figure 6), and likely result from major differences in productivity.

Russia had the largest forestland footprint in 2011 at 307.6 Mha, down from 425.3 Mha in 1995 (-28%). This is significant as few regions together dominate the global footprint. Russia is responsible for 23% of the 2011 global forestland footprint, followed by RoW Africa (141.8 Mha, 11%) and RoW America (141.5 Mha, 11%) and China (133,8 Mha, 10%). These four regions together represent 55% of the total footprint. While Brazil (120.9 Mha) and the USA (117.8 Mha) also have significant footprints, all other regions consume much less embodied forestland, as RoW Asia-Pacific follows at 62.4 Mha. The EU has the 7th largest household forestland footprint (89.9 Mha), making it a much smaller contributor than for timber, owing to its higher productivity.

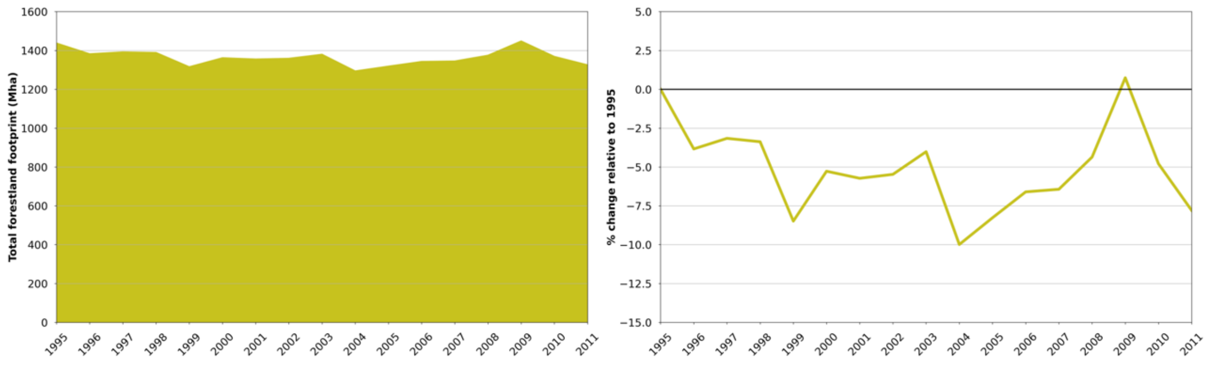

Figure 10. (a) Evolution of the forestland footprint of global household consumption (million hectares) over the period 1995-2011, (b) Percentage change of forestland footprint of global household consumption relative to 1995.

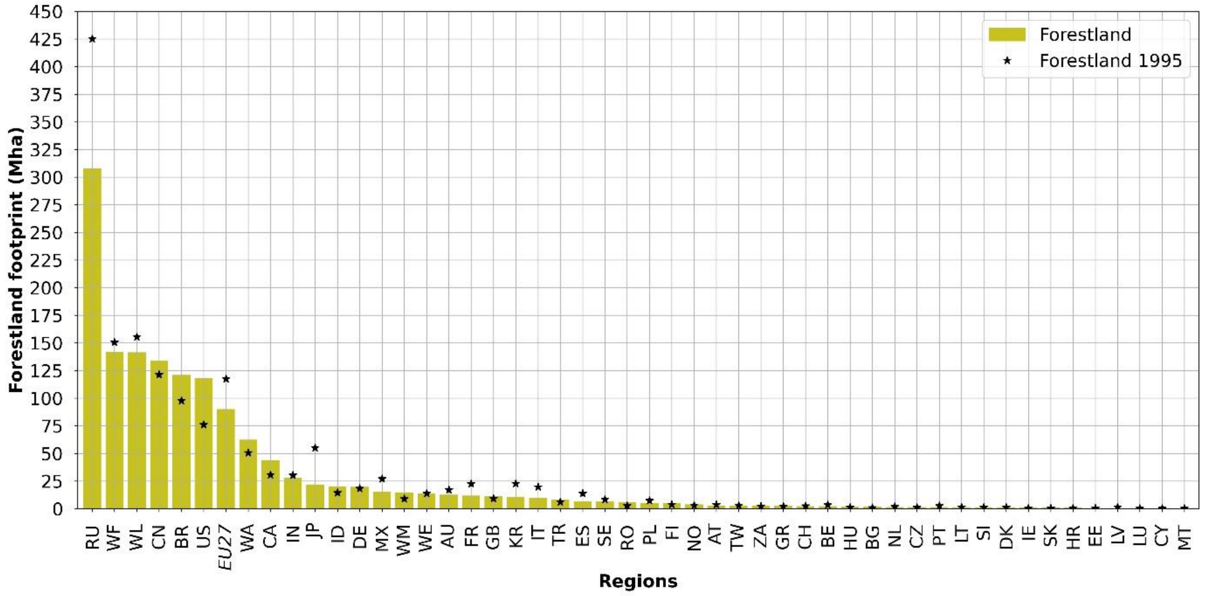

Figure 11. Regional forestland footprints of household consumption (million hectares) in 2011 versus 1995.

4.1.7. Trade of forestland embodied in household consumption

4.1.7.1. Imports and exports of embodied forestland

Similar to timber, trade flows play an important role in the forestland embodied in regions' household consumption, sourced both domestically and abroad. The increased role of trade and globalization since 1995 is evident in 34 out 49 regions increasing their imports of embodied forestland, and 35 out of 49 regions increasing their exports.

As shown in Figure 12 (or Appendix Figure A-5), a limited number of countries import much more embodied forestland to satisfy their household consumption than others. Out of the 49 regions in this study, 40 regions imported less than 10 Mha in 2011, and 35 imported less than 5 Mha. Yet the largest importer of embodied forestland in 2011 was China with 73 Mha, followed by the USA (49.1 Mha). China imports more than three times as much as India and RoW Asia-Pacific (each 21.9 Mha), making the differences between countries even larger forestland than for timber. The EU is also a major importer at 37 Mha of forestland, although this is a 40% decrease relative to 1995. The ranking is mostly the same as seen for the timber embodied in imports (Figure A-5), although Japan and Germany switched positions.

The same is true for changes compared to 1995. Japan decreased the most, down from 48.9 Mha to 14.8 Mha, while France (-62%), Italy (-60%), South-Korea (-59%) and Spain (-64%) also all have much smaller imports of embodied forestland. The USA doubled its forestland imports from 24.7 Mha in 1995 (+99%), and India increased by 4111% up from 0.5 Mha in 1995. Notably, increases seen in Germany (+17%) and the UK (+26%) are much lower than for their timber imports. While still large, the same is true for RoW America (+116%) but the opposite is the case for RoW Middle East (+76%).

Exports of embodied forestland satisfying global household consumption (Figure 12 or Appendix Figure A-6) show larger differences with timber exports in 2011 (Figure 12 or Appendix Figure A-6). A limited number of regions is responsible for large exports of embodied forestland, as 39 out of 49 regions exported less than 5 Mha. The largest exporters are RoW Asia-Pacific (60.7 Mha) and Russia (59.6 Mha). Particularly Russia is notable as it ranks 6th for timber embodied in exports, compared to 2nd for forestland. Other major exporters include Canada (30.6 Mha), RoW Africa (28.5 Mha) and China (26.8 Mha). Canada and Australia also rank relatively high compared to the timber embodied in exports. The opposite is true for regions such as RoW Africa and India.

The EU is meanwhile a less prominent embodied forestland exporter at 12 Mha (+50%), compared to its timber exports, likely for productivity reasons.

Changes in embodied forestland exports are similar to timber exports, although the extent of change differs. Indonesia decreased from 28 Mha in 1995 to 3.8 Mha (-87%) in 2011. Interestingly, RoW Africa went down from 42.7 Mha (-33%) in 1995, which is more than the change in timber exports. On the other hand, Canada went down from 35.7 Mha (-14%) in 1995 and the USA from 25.5 Mha in 1995 to 20.7 Mha (-19%) in 2011, both decreasing relatively less than their timber exports. Increases are particularly seen in Russia, up from 1.6 Mha (+3528%) in 1995, but also China up from 4.7 Mha (+468%) and RoW Asia-Pacific up from 48.9 Mha (+24%). China exported relatively more forestland than timber, while the opposite is true for Russia.

4.1.7.2. Trade balance of embodied forestland

The trade balance of forestland embodied in household consumption (Figure 12) indicates the distinction between net importers and exporters is even stronger for forestland. The top 5 largest net exporters consists of low- to medium-income regions (Russia, RoW Asia-Pacific, RoW Africa and Brazil) and one high-income country (Canada), likely linked to their abundancy in forests. At +55.7 Mha, Russia exports significantly more than it imports, with the second spot already much lower for RoW Asia-Pacific at +38.8 Mha, and even lower for Canada (+24.8 Mha), RoW Africa (+22.7 Mha) and Brazil (+12 Mha).

Similar to the timber trade balances, particularly Indonesia (+26.8 Mha in 1995 to +2 Mha in 2011), but also RoW Africa (down from +32 Mha) and Canada (down from +32.1 Mha) became less prominent exporters of embodied forestland. All these regions, and especially Indonesia imported more and exported less. To a lesser extent, RoW America and Europe also became smaller net exporters. Russia grew the strongest from a position of net importer in 1995 (-5.4 Mha) to net exporter, with a much larger change compared to the timber trade balance. RoW Asia-Pacific also grew a lot, up from +23.7 Mha in 1995. In both cases this mostly resulted from rising exports.

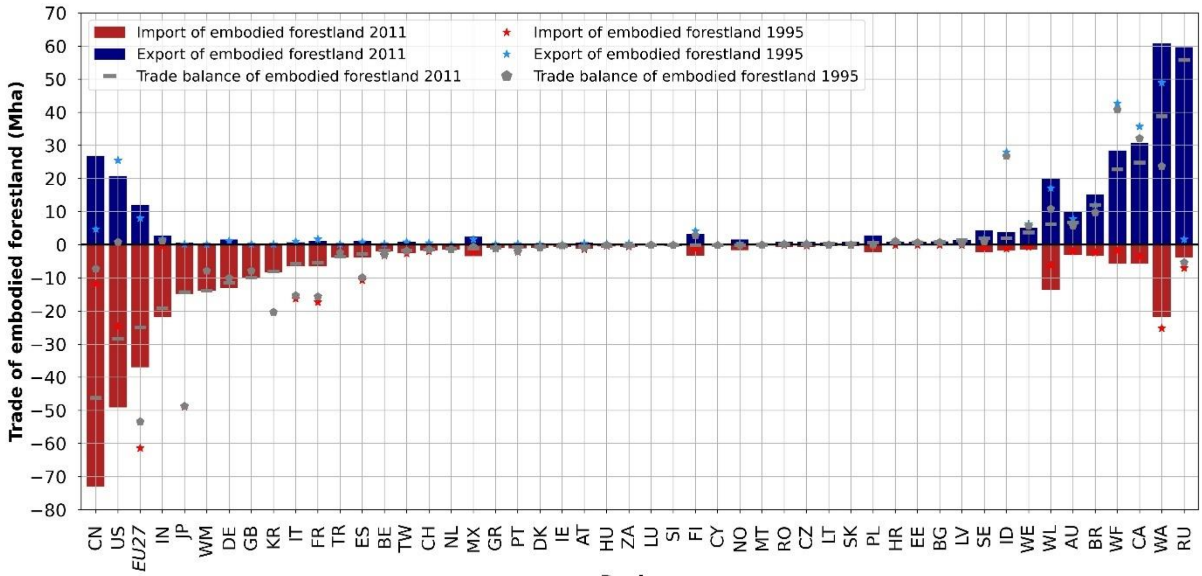

Figure 12. Imports, exports and trade balance of embodied forestland (million hectares) to satisfy household consumption in 2011 compared to 1995. Regions sorted from net importers (left) to net exporters (right).

The differences between top net importers of embodied forestland are notably larger than for embodied timber. The top 5 net importers provide a mixed picture of low- to medium-income countries (China, India, RoW Middle East) and high-income countries (USA, Japan). Overall, higher income countries tend to be net-importers, although emerging economies with more limited resources (e.g. China, and particularly India) are also net importers. China is the largest net importer at -46.2 Mha, with much lower in second place the USA at -28.4 Mha and even lower India at -19.2 Mha. Japan (-14.3 Mha) and RoW Middle East (13.8 Mha) close the top 5. The EU is also a major net importer at +24.9 Mha, but through increases in exports and decreases in imports, this is still an increase of 28.4 Mha relative to 1995.

Similar to the timber trade balance, strong decreases are seen for Italy, South-Korea, France and Spain, again related to their overall decreased imports of embodied forestland. Japan also dropped a lot, down from -48.8 Mha. Multiple regions became net importers since 1995, such as the USA up from +0.8 Mha and India, up from +1.2 Mha, which were both more neutral compared to their timber trade balances. China saw the largest change, up from -7.2 Mha in 1995. For China and India, these changes are likely explained by their role as major emerging economies.

4.1.7.3. Displacement of household forestland footprints

Countries displaced on average 52% of their household forestland footprints in 2011, 10% more than in 1995. Out of 49 regions, 36 increased their dependency on foreign forestland (Figure A-9). Dependency on displacements generally increased for high-income countries, emerging economies and regions with limited resources, similar to the timber footprint. However, the share of displaced forestland is for most countries larger than the share of displaced timber in their footprints (Appendix Figure A-8). This indicates that countries often displace to nations with lower timber productivity, although Norway, Australia, Greece, Italy and Japan form exceptions.

Similar to timber, Malta, Luxembourg, the Netherlands and Cyprus displace more than 99% of their footprint. The UK, RoW Middle East, Denmark, Belgium and Taiwan also have very high dependencies at more than 90%. Twenty-four regions meanwhile displace more than 50% of their footprint (16 in EU, 18 in Europe).

The EU overall displaced 41% of its household forestland footprint in 2011. Although a decrease of 11% relative to 1995, this is much larger than the 27% displacement of the EU timber footprint, indicating sourcing countries have lower productivity.

4.1.7.4. Bi-lateral trade flows of embodied forestland

Five regions (aggregated as in Table 5) provide 74% of the global forestland for household consumption (Figure 13). Russia alone provides 27%, followed by Africa (RoW Africa + South-Africa) (13%), America (12%), Asia-Pacific (12%) and Brazil (10%). Meanwhile, five regions consume 66% of the global embodied forestland. This is led by Russia (23%), followed by America (12%), Africa (11%), China (10%) and Asia-Pacific (10%). Particularly dependent upon imports are China (55% of its footprint), the USA (42%) and the Asia-Pacific region (30%). A remarkable reduction of imports is seen in the EU (-40%) and Russia (-45%) alongside Asia-Pacific (-9%), while other regions strongly increased their displacements. Out of the supplying regions decreases are seen in Africa (-33%), USA (-19%), Canada (-14%) and non-EU Europe (-8%), while in particular Russia (+3528%), China (+468%) and Asia-Pacific (+120%) became much more prominent exporters.

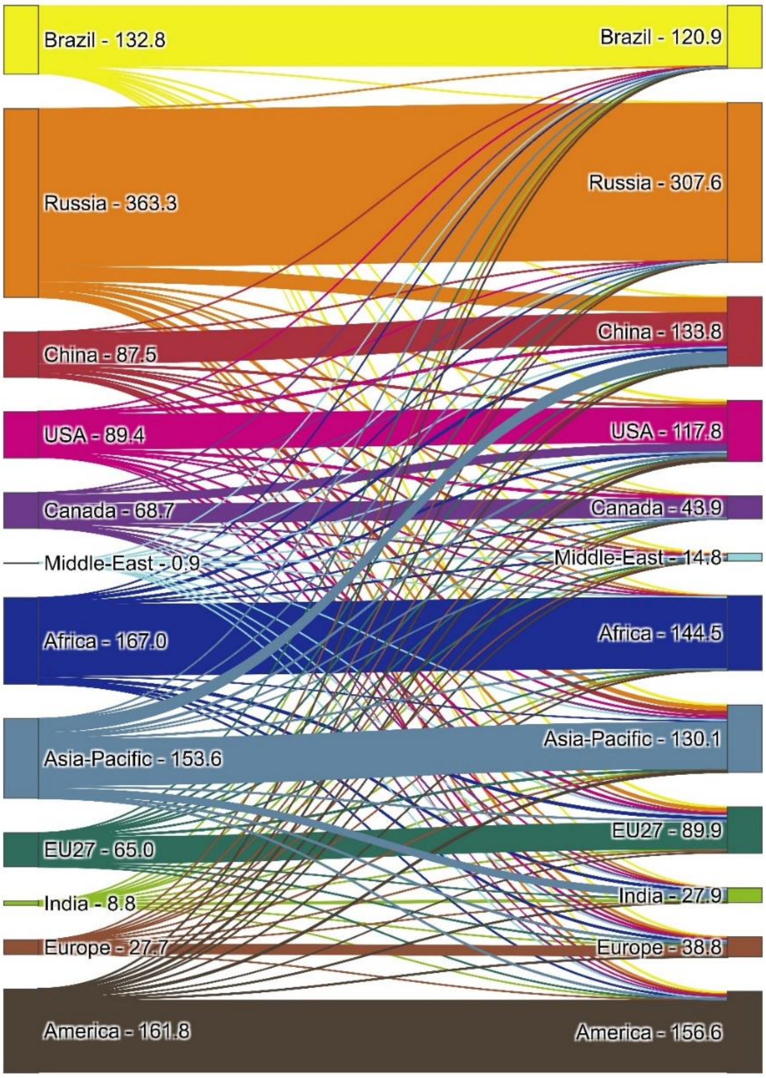

Figure 13. Trade flows between major sourcing regions (left) and major consumers (right) of embodied forestland (million hectares) in 2011. Regions aggregated as in Table 5.

Although the Asia-Pacific region (62.6 Mha) supplied the most embodied forestland, Russia as the second largest exporter (59.6 Mha) strongly deviates from the timber figures. About half of this forestland is embodied in products consumed by Chinese households (29.5 Mha).

Out of the importers of embodied forestland, China displaces the most forestland (73 Mha or 55% of its total forestland footprint), particularly to Russia (29.5 Mha), followed by Asia-Pacific (25.5 Mha), together more than two thirds of its displacements. Yet, for timber, Russia had a much less prominent role in the Chinese footprint.

Similar to the imports of embodied timber, the USA is the second largest importer of embodied forestland at 49.1 Mha (42% of its footprint). This forestland is also for a large part imported from Canada (17.2 Mha), although the relative role of the America region (7.6 Mha) becomes larger for forestland, followed by Asia-Pacific staying similar (6.4 Mha). China notably plays a particularly smaller role in the forestland footprint of the USA (6 Mha). Asia-Pacific is the third largest importer of embodied forestland (39 Mha or 30% of its footprint). Compared to its timber displacements, especially Russian forests (9.4 Mha) are more important, while Chinese forestland (9 Mha) contributes less.

The EU27 displaced 37 Mha of forestland, equal to 41% of its forestland footprint. Forestland is supplied by multiple regions, especially Russia (7.8 Mha) and Africa (7.1 Mha). Relative to 1995, when the EU displaced 61.4 Mha, a large reduction occurred (see Figure 13 and Appendix Figure A-12). A lot less forestland was displaced to Africa (29.6 Mha in 1995) and to the USA (2.5 Mha down from 6.8 Mha) and Canada (1.5 Mha down from 8.1 Mha). Major increases occurred for displacements to Russia (up from 0.6 Mha), China (3.7 Mha up from 0.3 Mha) and non-EU Europe (3.8 Mha up from 1.2 Mha).

Similar to the timber figures, India closes the top 5 importers of embodied forestland (21.9 Mha) with a very large 78% of its footprint. Again, dependency on Asia-Pacific forests is shown, importing 15.5 Mha from this region. Europe (17.8 Mha) spreads its imports although most comes from the EU27 (4.1 Mha). America (16.3 Mha) imports most embodied forestland from the same continent (Brazil 5 Mha, USA 3.5 Mha, Canada 1.1 Mha). This is also visible for Canada at 5.8 Mha (3.1 Mha coming from USA), while Africa spread its imports strongly at 6.1 Mha. Russia (3.9 Mha) and Brazil (3.3 Mha) import the least embodied forestland, although Brazil does import a relatively large 1 Mha from the America region. The Middle East again imports embodied forestland very globally, at 3.6 Mha from Asia-Pacific and 1.6 Mha from China and Russia, 1.3 Mha from the EU and 1.2 Mha from Brazil.

4.2. Forest footprints at a regional scale

4.2.1. Regional timber footprints of household consumption

4.2.1.1. Per capita timber footprints

The average timber footprint of household consumption was 0.58 m^3/cap in, with strongly varying footprints between regions (Figure 14). Including the population causes significant differences to total household timber footprints (Figure 6), with forest resource availability as major determinator for footprint size. There is no overall trend in the changes to timber footprints. The global average decreased slightly by 4%, and 25 out of 49 regions increased their footprint, while the remaining regions had a lower footprint in 2011 relative to 1995.

Fifteen regions exceed the global average footprint, and some considerably. The three largest per capita footprints are found in Scandinavia: Sweden (1.95 m^3/cap), Finland (1.82 m^3/cap), Norway (1.53 m^3/cap). Canada (1.45 m^3/cap), Slovenia (1.37 m^3/cap) and Austria (1.36 m^3/cap) are some other regions with large footprints. Hence, the largest footprints are all found in Europe, except for Canada, and mainly in higher income countries rich in forests. The difference with the smallest footprints is large, and more mixed with India (0.08 m^3/cap), Indonesia (0.12 m^3/cap) and RoW Asia-Pacific and Cyprus (0.13 m^3/cap).

In 24 regions, the per capita timber footprint decreased, half of which in the EU. Some of the largest decreases relative to 1995 are found in Latvia (-1m^3/cap, -78%), Sweden (-0.63 m^3/cap, -25%), Japan (-0.54 m^3/cap, -70%), France (-0.52 m^3/cap, -48%) and Spain (-0.5 m^3/cap, -60%). In general, there does not appear to be a trend in specific regions reducing their footprints. The three largest contributors, all Scandinavian countries, show very different trends with Finland staying stable, Sweden decreasing its footprint and Norway increasing it. However, the overall footprint of the EU decreased by 17% to 0.57 m^3/cap, similar to the global average footprint.

Comparatively, relative changes are much larger in many regions with increasing per capita footprints, particularly in Bulgaria (+469%, +0.36 m^3/cap) and Luxembourg (+428%, +0.54 m^3/cap), which also saw the largest absolute increase. Other large increases are seen in Slovakia (+0.39 m^3/cap, + 275%), Croatia (+0.26 m^3/cap, +267%), Romania (+0.37 m^3/cap, +194%), Hungary (+0.3 m^3/cap, +104%) and RoW Europe (+0.18 m^3/cap, +103%). Hence, except for Luxembourg, particularly regions in eastern and southeastern Europe have seen the largest relative increases in per capita timber footprints. The same is visible for absolute changes, although Norway still noted the second largest increase at +0.53 m^3/cap (+52%).

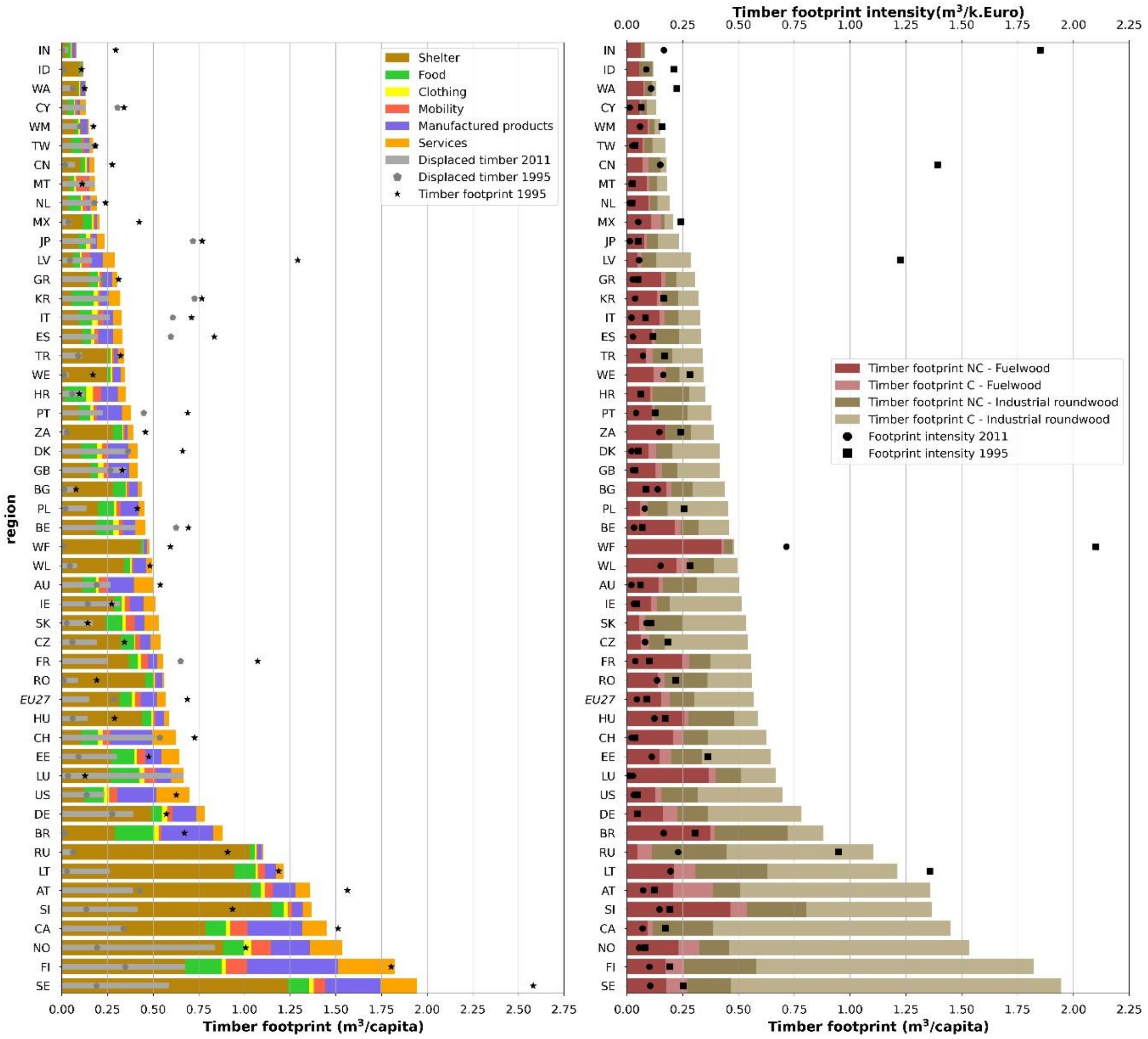

Figure 14. (a) Regional per capita timber footprints of household consumption, contribution of different product categories, displacement of timber footprints and changes between 1995 and 2011, and (b) contribution of different timber categories to household timber footprint and footprint intensity. C = coniferous, NC = non-coniferous.

4.2.1.2. Contributions of timber categories to per capita footprints

A comparison of per capita footprints (Figure 14) and total household timber footprints (Figure 6) further stresses how a few countries drive the world's fuelwood consumption. While 52% of the global timber footprint (Figure 4) is fuelwood, the global per capita average is 0.18 m^3/cap, or just 32% of the 0.58 m^3/cap global average timber footprint. This also indicates regions with large population (e.g. RoW Africa, India, China) are consuming the most embodied fuelwood, while their per capita footprints are not specifically large. As mentioned before (Figure 3), higher incomes tend to increase the share of industrial roundwood in timber footprints.

Some of the largest consumers of industrial roundwood are Sweden (1.68 m^3/cap, 86% of its footprint), Finland (1.57 m^3/cap, 86%), Canada (1.33 m^3/cap, 92%), Norway (1.21 m^3/cap, 79%) and Russia (0.99 m^3/cap, 90%). Meanwhile, the largest fuelwood footprints are found in Slovenia (0.54 m^3/cap, 39%), RoW Africa (0.44 m^3/cap, 91%), Luxembourg (0.40 m^3/cap, 60%), Brazil (0.39 m^3/cap, 45%) and Austria (0.39 m^3/cap, 28%).

Figure 15 furthermore suggests that higher income regions tend to have larger shares of industrial roundwood in their timber footprint, while the fuelwood share tends to be higher for lower income regions. This is not without exceptions, the clearest being Luxembourg with a high fuelwood share despite its very high income level. Some of the largest shares of fuelwood in regions' footprints are found in lower income regions such as RoW Africa (91%), India (79%), Mexico (74%) and RoW Middle East (68%). The highest shares of industrial roundwood, however, show a more mixed pattern with Canada (92%), Russia (90%), Sweden (86%), Finland (86%) and Slovakia (85%).

Shares of coniferous versus non-coniferous timber are mostly tied to the geographic region. High coniferous shares are for example found in Sweden (1.58 m^3/cap, 81%), Norway (1.17 m^3/cap, 76%) and Austria (1.03 m^3, 76%). Non-coniferous timber meanwhile dominates in regions such as Indonesia (0.11 m^3/cap, 96%), RoW Africa (0.46 m^3/cap, 96%) and India (0.08 m^3/cap, 91%). Yet, the EU's non-coniferous share is 53% and multiple high-income regions (e.g. Luxembourg, the Netherlands, Belgium, France) have high shares (>60%). This is likely at least partially linked to displacements to tropical areas.

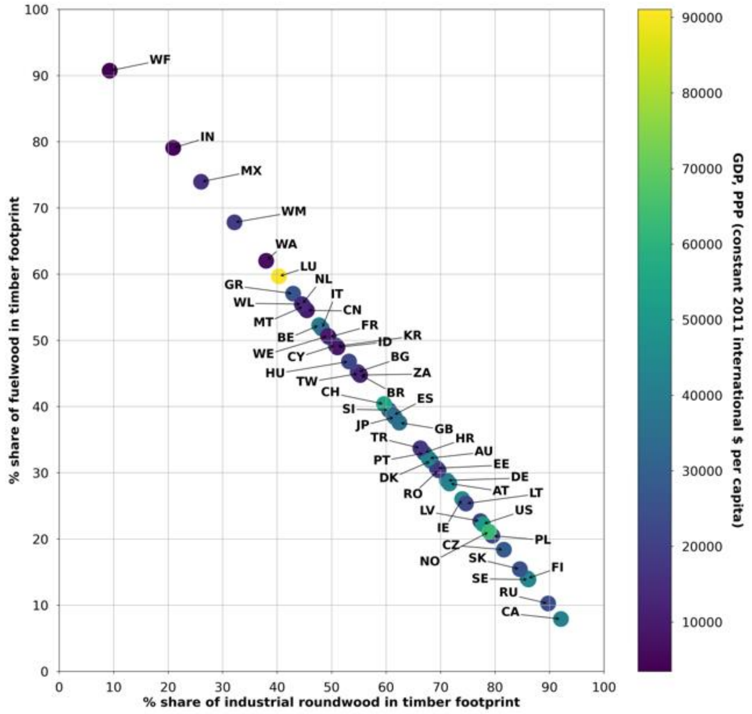

Figure 15. Share of fuelwood versus industrial roundwood in the household timber footprint of 2011 for all 49 regions, in relation to income level (GDP PPP constant 2011 international $ per capita).

4.2.1.3. Displacements of timber footprints

Most regions in this study (35 out of 49) increased their footprint displacements relative to 1995, elevating pressures on global forests. On average, countries displaced 0.23 m^3/cap, which is an increase of 16%.

The largest displacements in 2011 were found in Norway (0.84 m^3/cap), Finland (0.67 m^3/cap), Luxembourg (0.67 m^3/cap) and Sweden (0.59 m^3/cap). Notably, these regions all displace more than the global average household timber footprint. The smallest displacements are meanwhile found in regions such as RoW Africa (0.01 m^3/cap), Indonesia (0.01 m^3/cap), Brazil, South-Africa and India (all 0.03 m^3/cap).

Overall, mainly European higher income countries displace the most. Interestingly, this appears to include countries with a lot of forest resources. This is further supported by Switzerland (0.51 m^3/cap), Austria (0.39 m^3/cap) and Canada (0.33 m^3/cap) displacing more than average. Such trend suggests high-income countries have a choice rather than a need to displace more. The

EU's declining displacement (-46%) to 0.15 m^3/cap while 19 out of 27 Member States increased displacements however indicates that this could also result from increased EU-trade.

The largest decreases and increases however occurred both in high-income countries. Norway (+0.65 m^3/cap), Luxembourg (+0.63 m^3/cap), Sweden (+0.4 m^3/cap) and Finland (+0.33 m^3/cap) increased the most. Japan (-0.53 m^3/cap), South-Korea (-0.47 m^3/cap), France (-0.4 m^3/cap) and Spain (-0.4 m^3/cap) decreased the most. However, trade is at least within the EU likely more local in 2011 compared to 1995 considering the EU's strongly decreasing displacements.

4.2.1.4. Timber footprint intensities

The global average footprint intensity decreased strongly from 0.3 to 0.09 m^3/k.Euro (-70%) between 1995 and 2011. Such decrease occurred in all regions but Bulgaria (0.14 m^3/k.Euro, +62%) and Luxembourg (0.03 m^3/k.Euro, +239%), while Croatia remained stable (0.06 m^3/k.Euro). Despite overall efficiency gains - manifested in lower intensities - timber footprints decreased in only 24 regions.

Most regions (32 out of 49) have an intensity below 0.1 m^3/k.Euro. The lowest intensities are found in Cyprus (0.01 m^3/1000 Euro), Japan (0.01 m^3/k.Euro) and the Netherlands (0.01 m^3/k.Euro), and in other high-income regions. At 0.04 m^3/k.Euro (-51%), the EU's footprint is overall more efficient than the global average.

Developing regions tend to have much larger intensities. Especially RoW Africa is notable at 0.71 m^3/k.Euro, followed by Russia (0.23 m^3/k.Euro), Lithuania (0.2 m^3/k.Euro), India (0.17 m^3/k.Euro) and Brazil (0.16 m^3/k.Euro). Finland, Sweden, Estonia and Lithuania are some of the higher developed regions with relatively high intensities (> 0.1 m^3/k.Euro). The regions with the largest intensities in 1995 (> 1 m^3/k.Euro) all went down strongly: RoW Africa (-66%), India (-91%), China (-89%), Lithuania (-86%) and Latvia (-96%), with no intensities above 1 m^3/k.Euro left in 2011. The large decreases in these low- to mid-income regions indicate reduced reliance on woody biomass in their household consumption.

4.2.1.5. Contributions of product categories to timber footprints

Relating the data on timber footprint composition (Figure 14) to income levels in Figure 16 provides insights into the different product categories driving household timber footprints. On average, 0.31 m^3/cap or 49% of the timber footprints of household consumption results from products consumed from the shelter category, mostly due to 'products of forestry'. Yet, shares of shelter range from 5% in Croatia, up to 93% in Russia.

Higher income regions tend to have much lower footprint shares of shelter compared to lower income regions. Shelter shares are generally high (more than 54% average) for low-income regions, With Brazil (33%) and India (34%) among the few exceptions. However, multiple high-income regions still have high shares of shelter, e.g. Austria (76%), France (66%), Sweden (64%) and Germany (63%). Sweden also has the largest absolute shelter footprint (1.24 m^3/cap) followed by Slovenia (1.04 m^3/cap) and Austria (1.04 m^3/cap).

Low- and middle-income regions such as Russia, RoW Africa, Slovenia, Romania and Indonesia all have high shares of shelter (>80% of footprint). RoW regions Europe, Americas and Asia-Pacific also all score relatively high.

Particularly consumption of timber through manufactured products (average 0.09 m^3/cap, 15% of footprint) and to a slightly lesser extent also services (0.06 m^3/cap, 11% averages), tends to increase with income. For manufactured products, the highest shares are found in Switzerland (36%), Portugal (36%), the USA (30%) and Australia (28%). Notable exceptions to the income trend are Brazil (32%) and India together with RoW Middle East (25%). Absolute footprints stress this trend with the largest figures for Finland (0.5 m^3/cap), Sweden(0.3 m^3/cap), Canada (0.3 m^3/cap), and Brazil (0.28 m^3/cap).

Mid- to high-income countries dominate the largest shares in services (average 0.06 m^3/cap or 11%), e.g. Cyprus (26%), USA (26%), Australia (22%), Latvia (21%) and Switzerland (21%). Yet, in absolute terms the largest services timber footprints occur only in high-income regions: e.g. Finland (0.31 m^3/cap), Sweden (0.2 m^3/cap), USA (0.18 m^3/cap). Exceptions are most notable for high-income regions such as Germany, France and Austria with very low services shares of 6%.

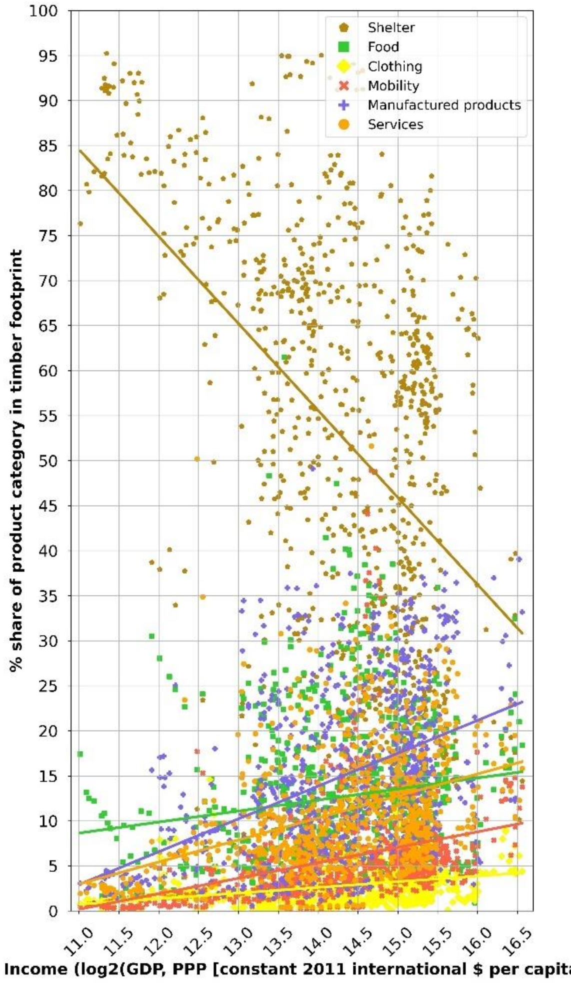

Figure 16. Shares of aggregated product categories in household timber footprints related to income level for all 49 regions over the period 1995-2011.

The income trend is still present, albeit less pronounced, for other categories. Contributions to timber footprints are the smallest for the clothing product category, at an average of 0.02 m^3/cap or 4% of footprints. Yet, the highest shares are still found in countries such as Croatia (11%), Italy (10%) and Japan (10%). The largest footprints are only 0.04 m^3/cap (Croatia, Norway)

Higher developed regions tend to have higher shares of the mobility category in their footprints, more so than is the case for clothing, although shares are on average relatively low at 6% (0.03 m^3/cap). Malta has a remarkably high share of 35% of its timber footprint for mobility. Other high shares are found in Latvia (16%), the Netherlands (13%), Croatia (13%) and Cyprus (11%). Footprints of about 0 m^3/cap occur, and are all found in lower income regions (e.g. Indonesia, India, RoW Africa, RoW Asia-Pacific). Finland (0.12 m^3/cap), Norway (0.11 m^3/cap), Canada (0.09 m^3/cap) are meanwhile high-income countries with the largest mobility timber footprints.

For the food product category (average 0.07 m^3/cap or 15% of footprints), some regions have very large shares in their timber footprints, with South-Korea (38%), the Netherlands (36%), Taiwan (33%) and Croatia (33%) all having shares above 30%. Eight more countries have shares above 20%: Cyprus, Brazil, India, Mexico, Luxembourg, Italy, Denmark and Belgium. This list is clearly mixed, further stressed by very low shares found in Austria (4%), Sweden (6%) and

Norway (7%) relative to the 15% (0.03 m³/cap) average, and Brazil having the highest per capita food timber footprint (0.22 m³/cap).

Interestingly, the EU follows all global averages for consumption categories, except for services (0.05 m³/cap, or 0.01 m³/cap lower).

At 1299 Mm³ in 2011, household shelter products consume 60% of the global timber (Figure 17). Other large product categories consume much less, e.g. manufactured products (307.7 Mm³) or food (234.5 Mm³). Out of the most consumed timber category, non-coniferous fuelwood, 66% (662.5 Mm³) is used by shelter products. Most of the timber from other categories is also consumed for shelter products.

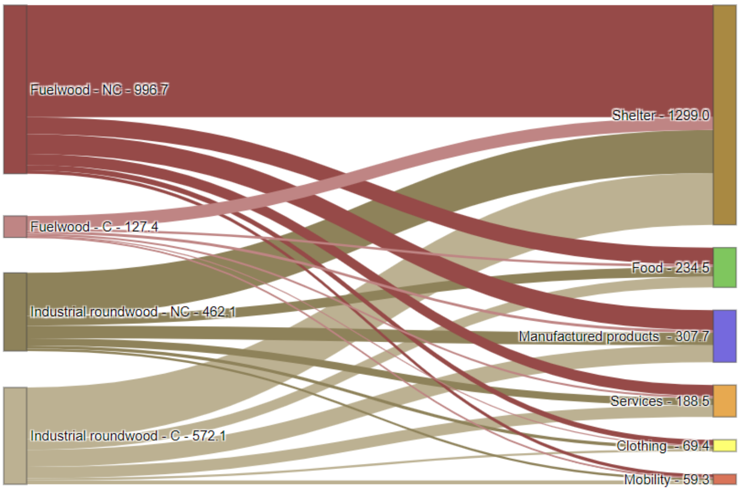

Figure 17. Sankey connecting the total global household consumption of four timber categories within the timber footprints to the consumption of different product categories (million m³) in 2011. C = coniferous, NC = non-coniferous.

Contributions of different timber categories (Figure 17) differ relatively strongly between product groups. Mobility (61%), services (59%), manufactured products (57%) and food (51%) rely mostly on industrial roundwood. Respectively they consume for 56%, 58%, 62% and 67% non-coniferous timber. Fuelwood has a share of 57% in the shelter product category, likely increased by household firewood consumption within this category, followed by clothing at 56%. Their respective consumption shares of non-coniferous timber are 71% and 72%. This indicates higher consumption of fuelwood correlates to higher non-coniferous timber consumption.

This link between fuelwood and non-coniferous timber likely results from earlier mentioned income correlations with fuelwood. Lower-income countries consuming the most fuelwood are generally also those where non-coniferous trees dominate, and with the least displacements.

4.2.2. Regional forestland footprints

4.2.2.1. Per capita forestland footprints

Differences between the largest per capita household consumers of embodied forestland and other regions (Figure 18) are larger than for timber, stressing a few regions affect forest biodiversity much more than others. Notably, countries with high forest resource availability dominate, rather than a mixed influence with income levels. The global average household forestland footprint in 2011 was 0.3 ha/cap and decreased by 14% relative to 1995. Despite this, still 22 out of 49 regions around the globe increased their forestland footprint by 2011.

The top 10 is clearly mixed in income levels. Russia's households consumed by far the most forestland at 2.15 ha/cap, while Canada's second-highest footprint is already much lower at 1.28 ha/cap. Scandinavian countries also have high footprints at 0.97 ha/cap for Finland, 0.77 ha/cap for Norway and 0.65 ha/cap for Sweden. Only 8 regions had forestland footprints larger than 0.5 ha/cap in 2011. Most of the regions (36 out of 49) had in fact forestland footprints smaller than the global average of 0.3 ha/cap, further stressing the discrepancy in global forestland pressures exerted by the largest consumers and other regions. Except for Mexico, the top 10 contains all other American regions: Canada, Brazil, the USA and RoW America. The EU27 in comparison has a smaller forestland footprint at 0.2 ha/cap, likely due to its high productivity.

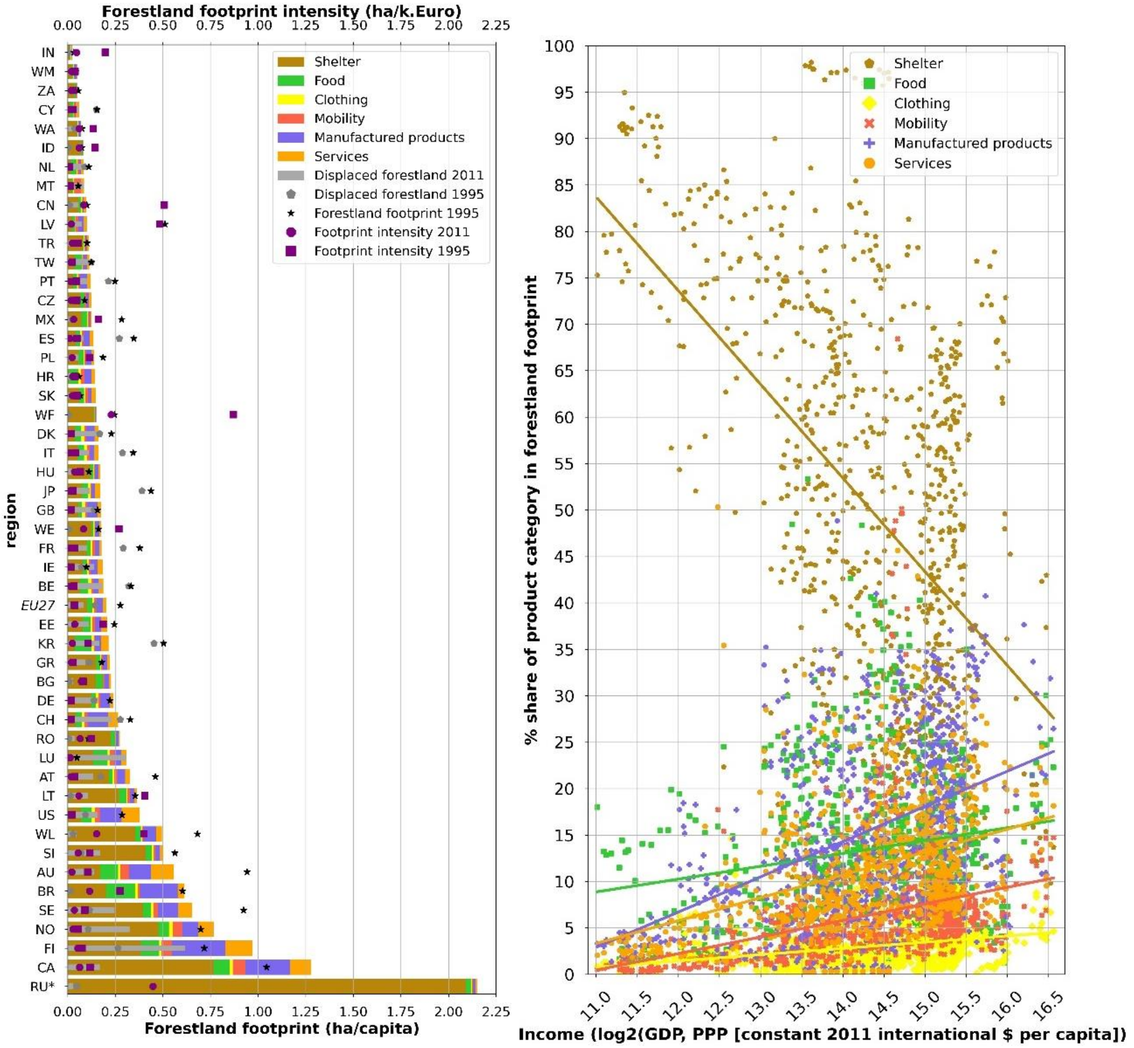

*Figure 18. (a) Regional per capita forestland footprints of household consumption, contribution of different product categories, displacement of forestland footprints, footprint intensities and changes relative to 1995 and (b) Shares of aggregated product categories in household forestland footprint related to income for all 49 regions over the period 1995-2011. * Russian forestland footprint and footprint intensity were respectively 2.87 ha/cap and 3 ha/k.Euro in 1995.*

Per capita forestland footprint reductions are seen both in the global average and in a bit more than half (27) of the regions. Indeed, Figure 18 confirms large decreases in per capita forestland footprints have occurred while increases were limited. The forestland footprint decreased more than 0.1 ha/cap in 14 regions. Russia had the largest decrease at -0.72 ha/cap (-25%), while regions such as Latvia at -0.41 ha/cap (-80%) and Australia at -0.38 ha/cap (-41%) also saw major decreases.

In comparison, only 5 regions noted increases larger than 0.1 ha/cap. This includes Bulgaria (+0.15 ha/cap or +208%), Romania (0.17 ha/cap or +153%), Canada (+0.23 ha/cap or +22%), Finland (+0.26 ha/cap or +36%) and Luxembourg with a 546% growth (+0.26 ha/cap) relative to 1995.

The EU27 per capita forestland footprint overall decreased by 26% (-0.07 ha/cap), a remarkable difference compared to the USA's 33% growth (+0.09 ha/cap). Yet it is worth noting that 13 out of 27 regions across the EU showed at least limited growth in their forestland footprint.

4.2.2.2. Displacements of forestland footprints

Displacement of forestland in the household forest footprints (Figure 18) meanwhile increased in most regions (32 out of 49) between 1995 and 2011. The global average displacement increased slightly from 0.1 ha/cap to 0.11 ha/cap (+6%), which combined with the lower average footprint translates to an increase in average displaced footprint from 42% to 52%. Out of 49 regions studies, 19 even exceeded the global average forestland displacement, most of which are high-income with some mid-income countries.

Finland displaced at 0.62 ha/cap the most forestland in 2011, which is almost double Norway's displacement of 0.32 ha/cap and Luxembourg's 0.31 ha/cap. Aside from Sweden (0.25 ha/cap) and Switzerland (0.23 ha/cap), countries displace less than 0.20 ha/cap. Thus, the largest per capita displacers are found in high-income regions, particularly Scandinavia, with a top 15 spread across Europe and North America. Lower income countries meanwhile displace much less forestland, e.g. RoW Africa, Indonesia and South-Africa at 0.01 ha/cap and Brazil, India and RoW Europe at 0.02 ha/cap.

Yet, both the largest decreases and increases occurred in higher income countries. The largest decreases are found in South-Korea (-0.29 ha/cap or -63%), Japan (-0.27 ha/cap or -70%), France (-0.19 ha/cap or -66%), Spain (-0.19 ha/cap or -69%) and Italy (-0.18 ha/cap or -62%). Particularly large increases are seen in Finland (+0.35 ha/cap or +134%), Luxembourg (0.29 ha/cap or +1763%) and Norway (+0.22 ha/cap or +204%). Sweden following at 0.13 ha/cap increase (+116%) again stresses the large displacements in Scandinavia.

The country-level trend (18/27 regions increased displacements) combined with the EU's overall decreased displacement (0.14 ha/cap to 0.08 ha/cap, -42%) and dependency on foreign forestland (52% to 41%), indicates increased displacement within the EU.

4.2.2.3. Forestland footprint intensities

The forestland footprints increased in 21 regions, despite decreases in the footprint intensity (Figure 18) in every region between 1995 and 2011, except for Luxembourg noting a very large growth of 315% from 0.003 ha/k.Euro to 0.013 ha/k.Euro. The global average intensity decreased a lot, from 0.18 ha/k.Euro to 0.046 ha/k.Euro (-75%), indicating much more efficient consumption of embodied forestland. The picture is largely the same for forestland as for timber.

The highest footprint intensities (> 0.1 ha/k.Euro) are however found in regions with lower incomes but also considerable forest resources: Brazil (0.114 ha/k.Euro), RoW America (0.151 ha/k.Euro), RoW Africa (0.228 ha/k.Euro) and especially Russia (0.448 ha/k.Euro).

Overall, the lowest footprint intensities (< 0.02 ha/k.Euro) are seen in 24 regions, with mostly higher income countries in western, central and southern Europe, Japan and the USA, but also Taiwan, South-Africa and RoW Middle East. The EU27's footprint intensity is rather low at 0.016 ha/k.Euro. Scandinavian countries, with large forestland footprints and a lot of forest resources, meanwhile have intensities in the middle of these values: Norway at 0.28 ha/k.Euro, Sweden at 0.035 ha/k.Euro and Finland at 0.054 ha/k.Euro.

4.2.2.4. Contributions of product categories to forestland footprints

On average, the shelter category represents 48% of the forestland footprints at 0.17 ha/cap. Especially Russia is interesting as its 97% share of shelter products causes a forest footprint of 2.1 ha/cap. Followed by Canada (0.77) and Norway (0.48 ha/cap), the shelter footprints quickly decrease. Regions such as RoW Africa (89 %), Indonesia (83%), Romania (83%) and Slovenia (81%) all have very high shelter shares, but their respective forestland footprints are rather low.

As seen in Figure 18, the share of product categories in the forestland footprint changes with the income level in a similar fashion as for timber products. As income increases, the share of the 'shelter' category tends to decrease sharply, while other categories gain importance. Within the EU, shelter is less important. On a global level, especially manufactured products tend to have larger shares for higher income levels, followed by services and mobility.

For manufactured products (average 0.04 ha/cap, 15% of footprints), this includes Switzerland (41%), Portugal (34%), the USA (30%), the UK (30%) and Finland (29%). Yet, Brazil also has a high share of manufactured products (32%), causing a footprint of 0.20 ha/cap. Finland's manufactured products cause the largest forestland footprint at 0.28 ha/cap.

Meanwhile, services overall contribute an average of 0.03 ha/cap or 11% to the forestland footprints. It is an important category in countries like the USA (25%), Cyprus (25%) and Australia (21%), although services again contribute the most in Finland at 0.14 ha/cap, followed by Australia at 0.12 ha/cap.

Mobility has an average share in forestland footprints of 6% or 0.01 ha/cap, with Malta having a high share of 40%. Absolute contributions are overall low, with the highest for Canada at 0.07 ha/cap.

Some increases in share together with income are also visible for food products (average 0.03 ha/cap or 15%), while the changes for clothing are rather limited. For food, the highest shares in the forestland footprint are found in South-Korea (40%), the Netherlands (35%), Taiwan (35%), Croatia (33%) and Cyprus (31%). In per capita contributions, Brazil's food consumption causes 0.15 ha/cap forestland footprint, followed by 0.10 ha/cap in Finland.

The average share of clothing in the footprints is 4% (0.01 ha/cap), with the highest only 11% in Croatia. The highest absolute contributions are all limited at 0.02 ha/cap (Norway, Brazil, USA, Croatia, etc.). Interestingly, in 16 regions clothing represents less than 0.005 ha/cap of the forestland footprint. For all other categories but shelter, very low footprints are generally found in lower income regions, but also in emerging economies.

4.2.3. Timber versus forestland footprints

Large differences can be seen in efficiencies of regional footprints in terms of hectare of forestland per m^3 timber embodied in household consumption (Figure 19). Particularly standing out is Russia, with a very high requirement of 1.95 ha/m^3. Only two other regions, Australia (1.1 ha/m^3) and RoW America (1 ha/m^3), required at least 1 ha/m^3. Out of 49 regions in this study, 45 regions needed less than 0.75 ha/m^3 and a majority (32 regions) even used less than 0.5 ha/m^3. On the other hand, South-Africa required the least forestland for its primary timber demand resulting from household consumption, at 0.13 ha/m^3. This is significantly less than in any other region. Relative to 1995, the majority of regions (33 out of 49) increased the efficiency of their footprints.

In general, the regions with lower and higher efficiencies are very mixed, although it is worth noting that the top 10 worst efficiencies contains only 1 EU country (Greece), while multiple American regions (RoW America, Canada, Brazil) are in this top 10, with Mexico closely following. In fact, the EU's efficiency is at 0.36 ha/m^3, ranking better than the global average of 0.5 ha/m^3.

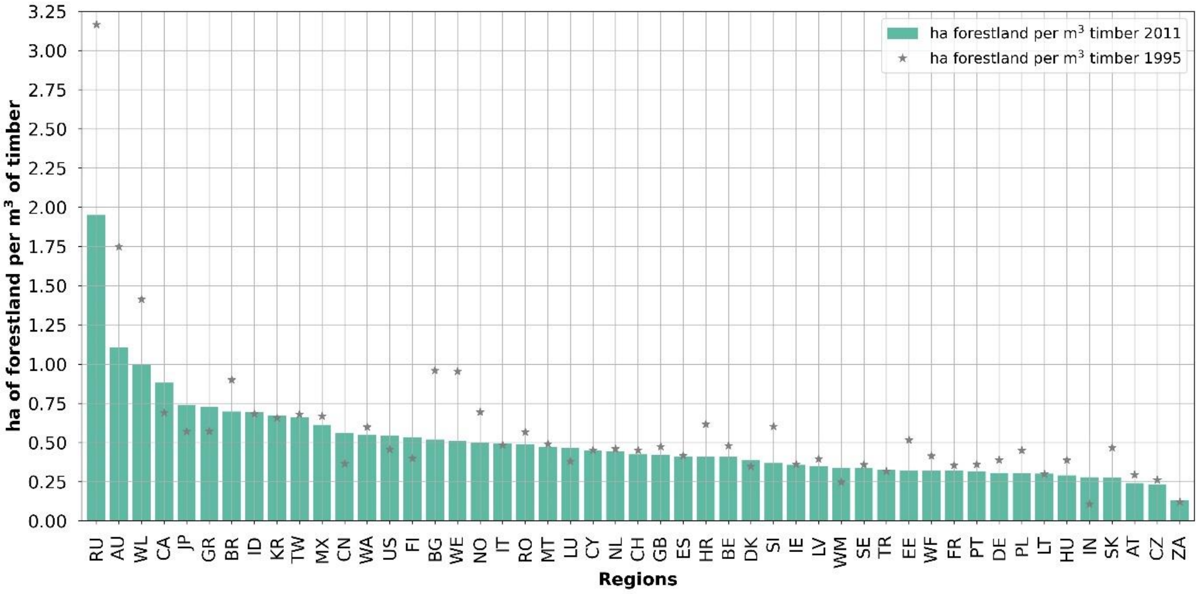

Figure 19. Ratios of regional household forestland footprints to timber footprints in 2011 and changes relative to 1995.

A comparison of the timber and forestland footprints in 2011 in relation to income (Figure 20) indicates rather weak income-driven differences in the forestland-timber footprint ratios provided in Figure 19. Yet, multiple of the highest timber footprints are found in higher income countries (e.g. top 6: Sweden, Finland, Norway, Canada, Slovenia, Austria). For forestland, the list of largest consumers is more mixed (e.g. top 6: Russia, Canada, Finland, Norway, Sweden, Brazil). However, the overall trend does not guarantee higher income determines higher forest footprints, suggesting other factors such as resource availability, culture, building practices, etc. play a role.

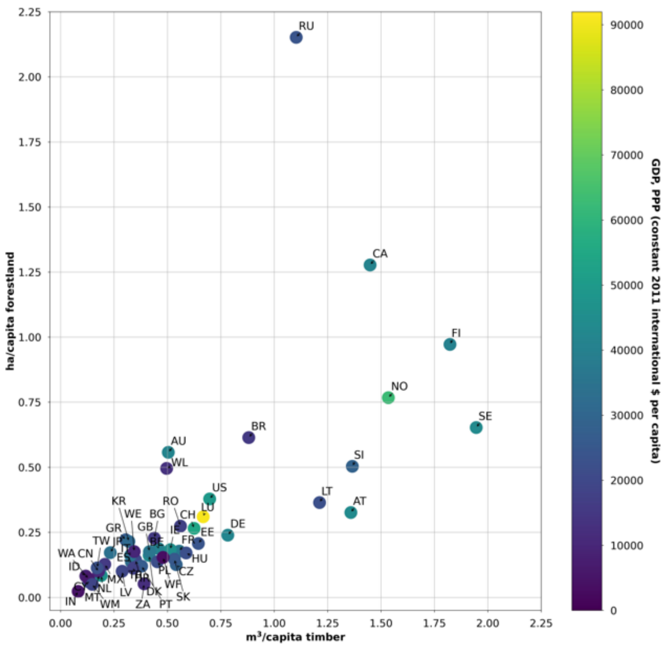

Figure 20. Household forestland footprint (ha/capita) versus timber footprint (m³/capita) in 2011 for all 49 regions, in relation to income level (GDP PPP constant 2011 international $ per capita).

4.3. Product hotspots for household footprints

4.3.1. Top 10 products in the global timber and forestland footprints

A limited number of product categories drives the global footprint of household consumption in 2011 (Table 7). In total, the top 10 product groups cause a timber footprint of 1702.5 Mm^3, which equals 79% of the total of 2158.4 Mm^3. The top 10 forestland consuming products represent a slightly higher 82% of the forestland footprint at 1085.8 Mha. The product groups and order thereof is almost identical, even in the top 20 (Table B-1, Table B-2), except for 'tobacco products' which is present in the top 20 for the timber footprint but replaced by 'vegetables, fruit and nuts' in the forestland footprint.

At about 50% or 1069.1 Mm^3 of households' global timber footprint, 'products of forestry' is the largest product group. With a 56% share (743.2 Mha), this is even more the case for the forestland footprint. This likely refers to high consumption of little processed woods, e.g. roundwood, but especially wood for burning as 60% of this product group consists of fuelwood.

Other products contribute significantly less to the global timber footprint. Other product groups with high footprints include paper (products) (119 Mm^3, 67.8 Mha), furniture and other manufactured goods (110.3 Mm^3, 55.8 Mha), food products n.e.c. ('not elsewhere categorized', 84.8 Mm^3, 48.9 Mha), real estate services (69.3 Mm^3, 36.7 Mha) and wood and products of wood and cork (i.e. processed wood products, 69.1 Mm^3, 36.1 Mha). Contrary to products of forestry, this is largely due to industrial roundwood use. This logically follows from the product groups concerned as those closely related to (processed) wood and derivates thereof have the highest footprints, although this is less evident for food products.

Table 7. Contributions of top 10 EXIOBASE product categories to the global timber and forestland footprints of household consumption in 2011.

	Industrial roundwood (Mm^3)	Fuelwood (Mm^3)	Total timber FP (Mm^3)	% share total timber FP	Forestland FP (Mha)	% share forestland FP
Products of forestry, logging and related services	431.5	637.6	1069.1	50%	743.2	56%
Paper and paper products	70.5	48.5	119	6%	67.8	5%
Furniture; other manufactured goods n.e.c.	62.5	47.8	110.3	5%	55.8	4%
Food products n.e.c.	47.3	37.5	84.8	4%	48.9	4%
Real estate services	45.6	23.7	69.3	3%	36.7	3%
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	38.1	31	69.1	3%	36.1	3%
Health and social work services	36,4	17.6	54.1	3%	28.5	2%
Chemicals n.e.c.	21.7	25.8	47.5	2%	26.6	2%
Hotel and restaurant services	24.1	18.1	42.2	2%	23.3	2%
Wearing apparel; furs	16.4	20.7	37.1	2%	19.1	1%
Other products (aggregation of remaining 190 products)	240.1	215.8	455.9	21%	240.7	18%
TOTAL	1034.2	1124.1	2158.4		1326.5	

The EU figure (Table B-3, Table B-4) shows in comparison a significantly lower contribution of products of forestry (36% for timber, 32% for forestland). This category, similar to the overall EU footprint, consists for 55% of industrial roundwood, indicating fuelwood energy is less important than on a global level. Manufactured wood products (resp. 10% for timber footprint, 9% for forestland) and furniture (both 8%) contribute significantly more to the EU household footprint than at the global level. The role of paper products is meanwhile significantly lower at 3% of the EU timber footprint and 4% of its forestland footprint, likely because of higher recycling rates.

4.3.2. Changes in product category contributions to forest footprints

The shelter category is the only category with a decreasing contribution to the forest footprints between 1995 and 2011 (Table 8), and is thus also responsible for the smaller global footprint in 2011. Except for a small decrease for food products, all fuelwood decreases found in the global footprint (Figure 4) are related to the shelter category, and hence likely to less household fuelwood consumption ('products of forestry').

Although the footprint changes are the largest for clothing (+88% timber, +90% forestland), its contribution to global forest footprints is limited (69.4 Mm^3, 35.6 Mha). Particularly large is however the 44% increase in manufactured products to 307.7 Mm^3 of timber (or 165.7 Mha forestland, +38%).

The picture is very different for the EU (Appendix Table B-5) where only clothing increased. The picture of industrial roundwood and fuelwood is also very different, e.g. coniferous fuelwood increasing for shelter. Overall decreasing non-coniferous timber contributions furthermore stress the earlier mentioned trend of lower displacements.

Table 8. Contributions of aggregated product categories to the global timber and forestland footprints of household consumption in 2011 with changes relative to 1995.

	Shelter	**Food**	**Clothing**	**Mobility**	**Manufactured products**	**Services**	**TOTAL**
Industrial roundwood – Coniferous	306.3 Mm^3 (-9%)	62.8 Mm^3 (+31%)	12.4 Mm^3 (+94%)	22.8 Mm^3 (+22%)	100.1 Mm^3 (+32%)	67.8 Mm^3 (+37%)	572.1 Mm^3 (+7%)
Fuelwood – Coniferous	75.8 Mm^3 (-50%)	13.9 Mm^3 (+47%)	6.8 Mm^3 (+140%)	3.4 Mm^3 (+68%)	15.9 Mm^3 (+67%)	11.7 Mm^3 (+94%)	127.4 Mm^3 (-29%)
Industrial roundwood – Non-coniferous	254.4 Mm^3 (+16%)	57.7 Mm^3 (+54%)	18.4 Mm^3 (+170%)	13.3 Mm^3 (+34%)	74.4 Mm^3 (+78%)	44 Mm^3 (+60%)	462.1 Mm^3 (+35%)
Fuelwood – Non-coniferous	662.5 Mm^3 (-26%)	100.2 Mm^3 (-8%)	31.8 Mm^3 (+53%)	19.8 Mm^3 (+4%)	117.4 Mm^3 (+35%)	65.1 Mm^3 (+24%)	996.7 Mm^3 (-16%)
TOTAL timber footprint per category	1299 Mm^3 (-19%)	234.5 Mm^3 (+15%)	69.4 Mm^3 (+88%)	59.3 Mm^3 (+19%)	307.7 Mm^3 (+44%)	188.5 Mm^3 (+39%)	2158.4 Mm^3 (-4%)
TOTAL forestland footprint per category	863.4 Mha (-21%)	128.6 Mha (+21%)	35.6 Mha (+90%)	31.2 Mha (+11%)	165.7 Mha (+38%)	102 Mha (+38%)	1326.6 Mha (-8%)

4.3.3. Volumetric vs land per capita footprints of products in EU27

Plotting the timber volume vs forestland per product category for the EU27 in 2011 (Figure 21) shows that most products fit the trendline relatively well. Interestingly, the difference compared to the trendline differs per region. Deviations in footprint efficiency (forestland required for the timber consumption) are large in Russia for various products. Meanwhile, products in regions like Brazil and China perfectly follow the linear trendline (see Appendix Figure B-1 to Figure B-11).

The largest contributor to the footprints, 'products of forestry', was left out considering its very large contribution (0.205 m^3 and 0.065 ha per capita). Its relatively efficient requirement of forestland (see Table 9) is similar to the second largest contributor, 'Wood and products of wood and cork'. This category is responsible for 0.056 m^3 timber/cap and 0.017 ha forestland/cap, which as the figure indicates, is more efficient than the trendline suggests.

'Furniture; other manufactured goods n.e.c.' (not elsewhere classified) (0.044 m^3/cap, 0.016 ha/cap) and 'real estate services' (0.028 m^3/cap, 0.009 ha/cap) follow the trendline more closely. 'Food products n.e.c.' (0.023 m^3/cap, 0.010 ha/cap), 'paper and paper products' (0.018 m^3/cap, 0.008 ha/cap), 'hotel and restaurant services' (0.015 m^3/cap, 0.006 ha/cap) and 'wearing apparel; furs' (0.010 m^3/cap, 0.005 ha/cap) are some of the larger contributors to the EU's footprint requiring more forestland per cubic meter of timber footprint.

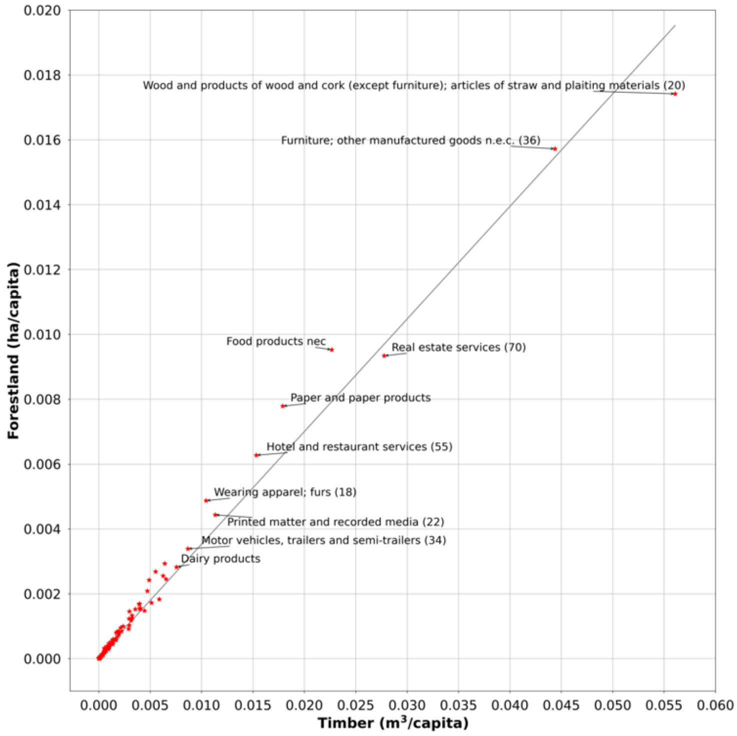

Figure 21. Per capita timber vs forestland footprints of EU27 household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry' (0.205 m³ and 0.065 ha per capita). Diagonal line represents trendline based on least squared linear regression.

When considering the efficiency of top products (forestland per m³ timber, Table 9), the categories most closely related to wood products tend to require less land per unit of timber. This is the case for 'wood and products of wood and cork' being the most efficient product category (0.31 ha forestland per m³ timber), followed by 'products of forestry' (0.32 ha/m³) and 'furniture; other manufactured goods' (0.34 ha/m³). An exception to this is 'paper and paper products', requiring 0.44 ha forestland per m³ timber. 'Wearing apparel' meanwhile ranks the worst, at 0.47 ha forestland per m³ of embodied timber.

Table 9. Product efficiencies (hectare/m³) for top 11 products in EU27 in 2011.

Product sector	**Efficiency (ha/m³)**
Wearing apparel; furs (18)	0,47
Paper and paper products	0,44
Food products nec	0,42
Hotel and restaurant services (55)	0,41
Printed matter and recorded media (22)	0,39
Motor vehicles, trailers and semi-trailers (34)	0,39
Dairy products	0,37
Furniture; other manufactured goods n.e.c. (36)	0,35
Real estate services (70)	0,34
Products of forestry, logging and related services (02)	0,32
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	0,31

For product categories with smaller footprints (Figure 22), multiple other products use more forestland than expected by the trendline. This includes 'textiles', 'rubber and plastic products', ‘leather and leather products’ and ‘radio, television and communication equipment and apparatus’.

Taken together with Figure 21, particularly clothing-related products (textiles, leather, wearing apparel/furs), as well as food products, rubber, plastics and paper products, put more pressure on forestland. This is likely linked to lower efficiencies from production in transition economies. Increasing globalization and outsourcing of production for these products hence poses a risk for exacerbation of pressures on forestland, which is especially likely to occur for clothing- and food-related products.

On the other side of the trendline, larger deviations can be seen particularly for ‘construction work’, but also ‘other services’ and ‘distribution and trade services of electricity’, all using less forestland than expected by the trend.

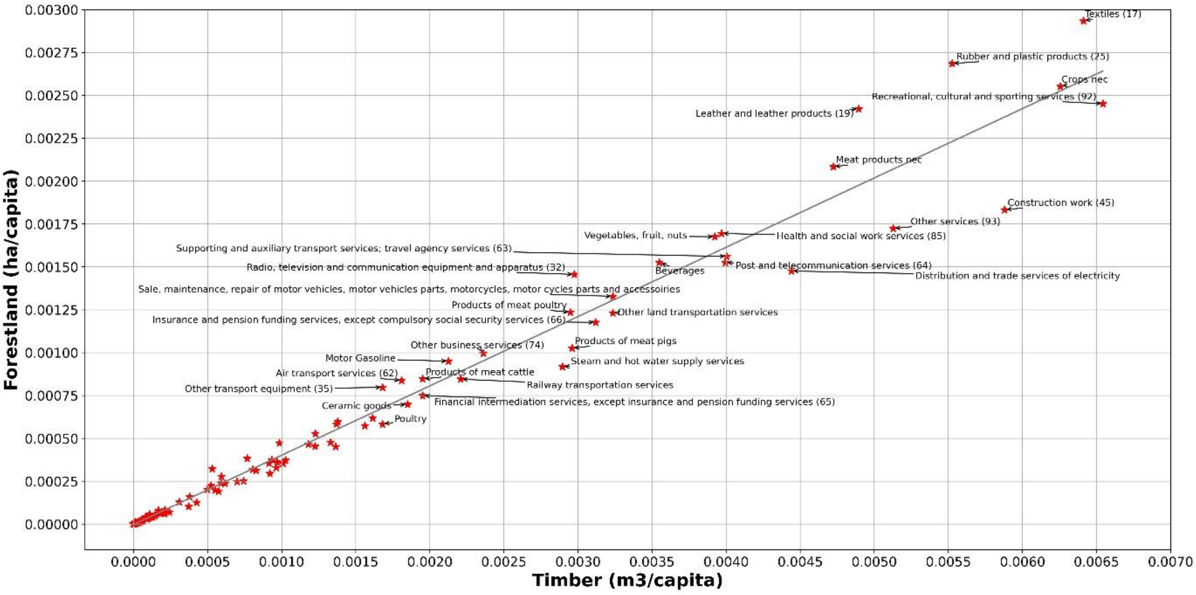

Figure 22. Per capita timber vs forestland footprints of EU27 household product consumption in 2011, without the 11 products with the largest timber footprints. Diagonal line represents trendline based on least squared linear regression.

4.3.4. Policy quadrants for timber and forestland footprints in EU27

One way to analyze the most relevant products for intervention, is through policy quadrants as shown in Figure 23. For timber, almost all products can be considered to be in the ‘low risk zone’. As products of forestry as a single category dominates the footprints and intensity (0.205 m^3/cap and 20.58 m^3/k.Euro), it has been left out of the figure in order to better analyze the other products. The intensity of this product group is very high, likely due to its nature as little processed timber. On a global scale, reducing fuelwood consumption could strongly reduce the timber footprint resulting from this category, while for the EU this is less clear due to higher industrial roundwood shares (Figure 14).

The graph further shows ‘wood and products of wood and cork’ having both a high timber footprint and footprint intensity. Its intensity being high is likely linked to this category consisting of processed wood products. Particularly for wood products, replacement of wood by other materials could reduce its intensity and timber footprint. This is a trend that seemingly already occurs for both wood products and products of forestry, as their intensity respectively dropped from 4.41 to 1.78 m^3/k.Euro and 20.58 to 14.86 m^3/k.Euro between 1995 and 2011. Such intensity decreases are in fact seen in most studied products (138 out of 200) in the EU.

The relatively low intensity but large footprint of 'furniture; other manufactured goods n.e.c.' indicates that reducing consumption seems favorable. However, the necessity of such products for shelter is likely high.

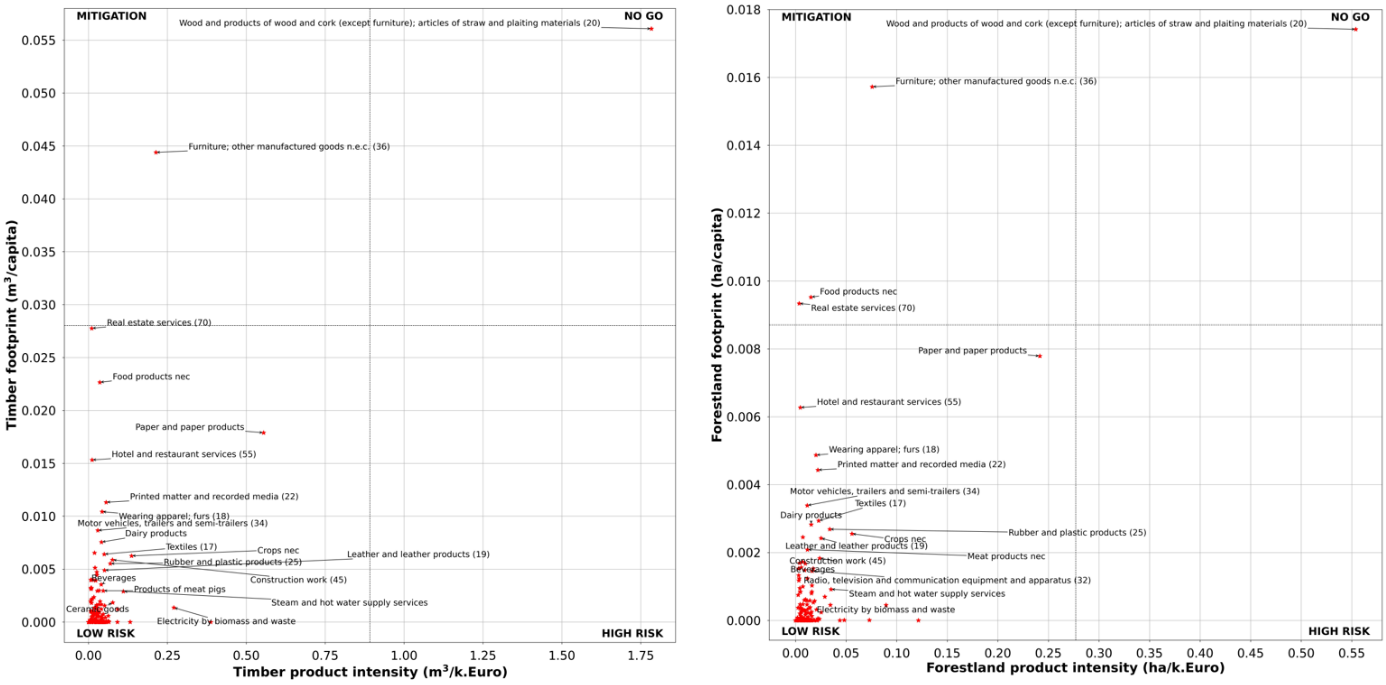

Figure 23. Timber (a) and forestland (b) footprint policy quadrant for product consumption by EU27 households in 2011, based on the per capita footprint and product intensity (footprint/1000 Euro). This graph does not include the largest category 'products of forestry' (0.205 m³/cap and 20.58 m³/1000 Euro for timber, 0.065 ha/cap and 4.71 ha/1000 Euro for forestland).

When considering the forestland policy quadrant, a similar picture exists for wood products, products of forestry and furniture. Yet, relatively seen, multiple products become even more relevant for mitigation. Food products are the clearest example, likely driven by timber consumption for products made in countries with lower timber production efficiencies. Reducing consumption of exotic products then becomes an option.

For paper and paper products, a risk can be seen in a diagonal move towards the 'no go zone' as forestland product intensities become higher along with the total footprint. A logical solution would be to increase the consumption of recycled paper products. Where possible, timber sources outside of the EU should be avoided as these likely further increase the demand for forestland.

In the case of real estate services and to a lesser extent hotel services, reductions of timber-based products seem desired to reduce footprints. Remaining products lean more towards the 'low risk zone', where consumption reductions and efficiency improvements generally have less of an effect. Yet, substitutions could still be beneficial.

5. Discussion

5.1. Summary of the results

5.1.1. The global scale

Household consumption was found to be responsible for 54% of the global timber and 60% of the global forestland footprints. Between 1995 and 2011, the household material footprint grew by 34% to 31.3 Gt, resulting from increasing biomass (+24%, 15.7 Gt) and minerals (+47%, 15.6 Gt) consumption. Yet, household timber consumption decreased by 4% to 1.36 Gt (4% of material footprint) or 2158 Mm³ in 2011. Within the household timber footprint, fuelwood decreased by

18%, while the industrial roundwood footprint increased by 18% to respectively 1124 Mm^3 and 1034 Mm^3. Primarily driven by the fuelwood decrease, non-coniferous timber decreased by 5% to 1459 Mm^3, while coniferous wood decreased by 2% to 700 Mm^3.

Top consumers RoW Africa (443.3 Mm^3), China (239.2 Mm^3), USA (217.5 Mm^3) and Brazil (173.5 Mm^3) are meanwhile responsible for 50% of the global household timber footprint. While the global household timber footprint declined, the growing role of trade is seen in most regions increasing imports and exports. Net exporters are generally abundant in forests, regardless of income levels (e.g. Canada, Sweden, RoW Africa, Russia), while net importers are industrialized (e.g. Japan, USA, Germany) and emerging (e.g. India, China) economies. High-income countries, emerging economies and countries with low resource availability have the highest dependencies on displacements, with an increasing average for timber of almost half the footprints (48%).

The African continent produces 25% of the global household timber, while the EU, China, USA and aggregated African and Asia-Pacific regions consume 64% of all timber. The EU mainly imports from Africa (22.9 Mm^3), China (8.6 Mm^3) and non-EU Europe, although its total displacements decreased by 44% to 67.1 Mm^3 in 2011. The largest EU exports go to non-EU Europe.

The total household land footprint remained fairly stable over time with 8315 Mha in 2011, caused for 55% by indirect use for forestry and agriculture and for 45% directly by households. Households' direct land footprint was very stable at 3754 Mha in 2011, mainly linked to subsistence farming (2929 Mha). The indirect land footprint decreased slightly (-4%) since 1995 to 4561 Mha in 2011, driven by the decrease in required forestland from 1439 Mha to 1327 Mha (-8%).

Top forestland consumer Russia (307.6 Mha) alone is responsible for 23% of the global household forestland footprint and its 28% decrease is the main reason for the declining footprint. RoW Africa (141.8 Mha), RoW America (141.5 Mha) and China (133.8 Mha) are other regions responsible for more than 10% of the total footprint. Similar to timber, the increasing trade is seen in regions' increasing imports (34/49) and exports (35/49) of embodied forestland. Top net importers (e.g. China, USA, India, Japan, Germany) and net exporters (e.g. Russia, Canada, RoW Africa) of forestland are similar to those of the timber footprint. Displacement dependency is on average 52%, and for many countries higher than for timber, indicating reliance on countries with worse productivity.

Out of the global forest area required for household consumption, Russia alone provides 27%, followed by Africa (13%), America (12%), Asia-Pacific (12%) and Brazil (10%). Russia also consumes 23% of the total forestland footprint, followed by America (12%), Africa (11%), China (10%) and Asia-Pacific (10%) regions. The EU displaced 27 Mha or 41% of its household forestland footprint, mostly to Russia (7.8 Mha) and Africa (7.1 Mha), although African displacements decreased, just as for timber.

5.1.2. The regional scale

The household timber footprint shows major differences between regions, with the largest consumers Sweden (1.95 m^3/cap), Finland (1.82 m^3/cap), Norway (1.53 m^3/cap) in stark contrast with low consumers India (0.08 m^3/cap), Indonesia (0.12 m^3/cap) and RoW Asia-Pacific and Cyprus (0.13 m^3/cap). Footprint size is related to income and resource availability, with the largest footprints found in high-income countries with abundant forest resources. Traditional dependency, e.g. in Brazil, does mean these factors do not guarantee footprint size. The EU's 0.57 m^3/cap nears the global average 0.58 m^3/cap, which is however exceeded by 15 out of 49 regions. Half of the countries reduced their footprint between 1995 and 2011, while the other half increased them, although EU timber per capita footprint decreased by 17%.

Within these footprints, higher income indicates higher shares of industrial roundwood, while the low per capita average share (32%) relative to the share in the total household footprint (52%)

stresses the large fuelwood consumption of few (low-income/emerging) countries. Non-coniferous timber consumption is found to be mainly linked to geographical location.

Differences are even larger for household forestland footprints, which both increased and decreased in about half of the regions relative to 1995. Russia has the largest footprint at 2.15 ha/cap, followed by Canada with a much smaller footprint at 1.28 ha/cap, Finland (0.97 ha/cap), Norway (0.77 ha/cap) and Sweden (0.65 ha/cap). This is much more than the smallest consumers India (0.02 ha/cap), RoW Middle East and South-Africa (both 0.05 ha/cap). Thirteen regions exceed the average of 0.3 ha/cap, while the EU footprint is much lower (0.2 ha/cap, -26%).

Most countries increased their displacement of timber (0.23 m^3/cap on average, +16%) and forestland (0.11 ha/cap on average, +6%). Displacements tend to be larger for high-income countries, including Scandinavian countries. This indicates factors other than forest abundance influence the dynamics e.g., cheaper labor and lax environmental laws. Likely due to increasing internal trade, the EU's timber (-46% to 0.15 m^3/cap) and forestland (-42% to 0.08 ha/cap) footprints decreased strongly and are lower than average.

Footprint intensities declined strongly in almost all regions (average 0.09 m^3 timber/k.Euro or -70%, and 0.013 ha forestland/k.Euro or -75%), indicating large efficiency gains. High-income countries have some of the lowest intensities, and developing regions some of the highest.

Low- to mid-income countries had the largest contributions of shelter in their forest footprints (average resp. 49% of timber and 48% of forestland footprint), although large absolute contributions are still found in regions with large footprints. Other product groups, such as mobility (both 6% average) and food (both 15% average), but particularly manufactured products (both 15% average) and services (both 11% average) increase with higher income, while clothing is the least important category (both 4% average).

5.1.3. Product hotspots

Only 10 products are responsible for 79% of the global household timber footprint and 82% of the household forestland footprint. The top 6 for both timber and forestland consumption is dominated by wood products and their derivatives. The aggregated 'products of forestry' is responsible for 50% (1069.1 Mm^3) of the household timber footprint and 56% (743.2 Mha) of the household forestland footprint. Other product groups derived from wood such as paper products (6% of timber footprint, 5% of forestland), furniture (resp. 5%, 4%) and other wood products (both 3%) also have relatively high contributions. Yet, relatively large consumption of wood also occurs for food products (4% timber and forestland) and real estate services (3%). Overall, changes over time indicate footprints only decreased because of lower fuelwood consumption, as all categories other than shelter increased between 1995 and 2011.

A hotspot for intervention is firstly products of forestry, consisting of wood fuels (60%) and little processed timber. In the EU, particularly manufactured wood products deserve attention due to their large footprint and intensity. Intensity in multiple other products such as furniture, food, and hotel/restaurant and real estate services is relatively low, making replaceability relevant. while the low intensity in furniture provides limited chances for mitigation. Furthermore, different clothing products, food, rubber and plastics require more forestland than expected, indicating the additional stress on forests from outsourcing such products.

5.2. Interpretation of the results

5.2.1. Global forest productivity

5.2.1.1. Available forest area for wood supply

The global household forestland footprint was 1327 Mha in 2011, and reaches 2214 Mha when considering all consumption categories. Comparing to the total global forest area of 4059 Mha in

2020 (FAO, 2020b), this indicates households require about 33% and total consumption about 55% of the global forest area. Both exceed the estimated designated forest area of about 1150 Mha in 2020 (FAO, 2020b), but FAOSTAT forestry data can be unreliable due to varying national definitions and lack of reporting (Bruckner et al., 2015; Fischer et al., 2017).

'Forest area available for wood supply' (FAWS) can provide more context as an estimate of productive forestland. O'Brien (2016) provides low (minimum literature or 75% of realistic), realistic (best estimate semi-natural + plantation forests) and high (all forest area except protected) estimates, which were compared to the forestland footprints in this thesis (Figure 24).

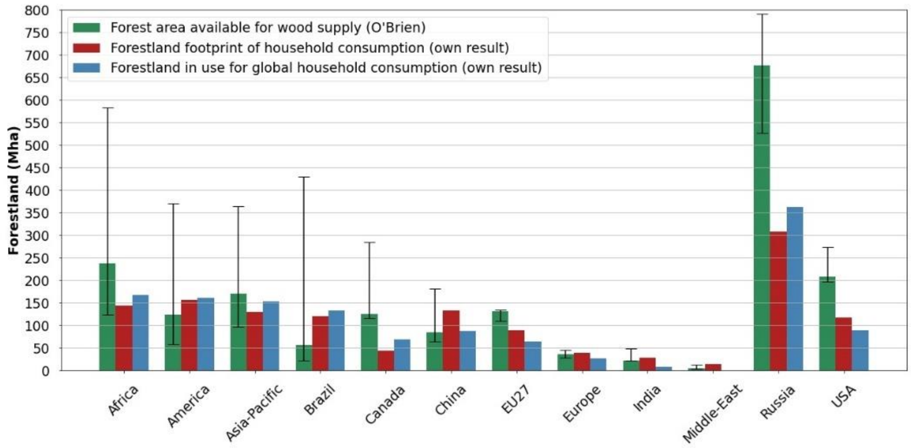

Figure 24. Comparison of forest area available for wood supply (O'Brien, 2016) to results on regionally aggregated footprints of household consumption and forest in use for global household consumption in 2011.

Available productive forestland is estimated at a realistic 1881 Mha (0.27 ha/cap) or high 3525 Mha (O'Brien, 2016). The 2011 household forestland footprint (1327 Mha or 0.19 ha/cap globally for 6936586070 people) comfortably fits within this realistic estimate, while the total footprint of 2214 Mha would exceed it. Although methods influence these estimates, a pattern of excessive use is to be expected as natural forest loss continues (FAO & UNEP, 2020). Additional pressures were found to mostly be driven by gross capital formation (30%), and thus production capacities.

Comparing the forestland footprints of the 12 aggregated regions, the largest forest user Russia along with the USA, the EU and Canada all have sufficient productive forest area available for both domestic and global household consumption, even using low estimates. Realistic estimates suffice for Africa and Asia-Pacific. Only Brazil (232% of realistic productive forestland), America (130%) and China (103%) have more forestland in use than realistically available. Although this could be related to the method in EXIOBASE 3 with used forests to various extents (Stadler et al., 2018b), it also indicates that wide-scale disturbances occur in these regions. Within the EU, this is also the case in Romania and Ireland, and furthermore in Japan and Australia. While no region exceeds the high estimates, this is an undesirable indicator as it would disturb all non-protected forests.

Global forest area in use for domestic household consumption exceed realistic availability in Brazil (212% of realistic productive forestland), China (158%), America (126%), Europe (109%), India (125%) and Middle East (331%). Hence, multiple regions need displacements as they would simply not have sufficient forestland. For the Middle East, even high estimates are insufficient.

5.2.1.2. Sustainability of timber footprints

The timber footprint can meanwhile be evaluated by comparing it to the net annual increment (NAI) of wood in each region (Egenolf & Bringezu, 2019; O'Brien, 2016). This is possible through multiplying the NAI ($m^3.ha^{-1}.year^{-1}$) with the realistic FLAWS of productive forest area (ha), providing the yearly timber productivity (See Appendix C for full explanation). This is shown in Figure 25. Sustainability of domestic production is then assumed when the domestic production of timber for global household consumption is below 100% of the NAI (as in Egenolf et al., 2021).

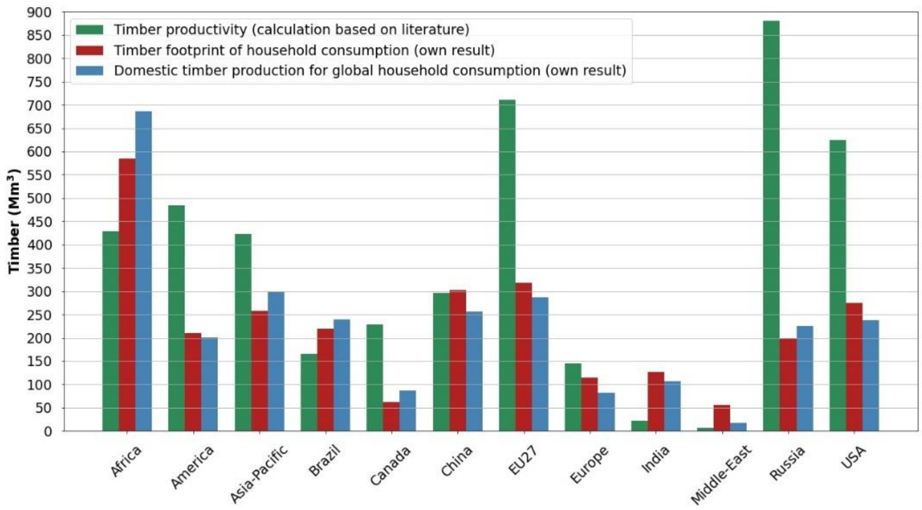

Figure 25. Comparison of regional timber production and household consumption in 2011 as calculated in this study to an estimated productivity as calculated from literature.

Summing up the productivity in all regions, the globally available timber at 100% NAI is 4415 Mm^3. This is on a global scale equal to a possible timber production of 0.64 m^3/cap at 100% NAI (for 6936586070 people in 2011), and similar to the sustainable supply range between 0.54 m^3/cap (80% NAI) and 0.68 m^3/cap (100% NAI) estimated by O'Brien (2016). It indicates the 2011 global household footprint of 2158 Mm^3 (or 0.31 m^3/cap) can easily be grown sustainably. Compared to a total global consumption of 3966 Mm^3 (0.57 m^3/cap), not much space for growth is left.

However, regional differences exist. Timber production for global household consumption can be called unsustainable in four regions: Brazil (144% of productivity at 100% NAI), Africa (160%), the Middle East (288%) and India (476%). Yet, O'Brien and Bringezu (2017) compare productivity at 80% and 90% NAI, as the forest structure is potentially harmed through a focus on short rotations which degrade forests and harm biodiversity at 100% NAI. At 80% NAI, China's timber harvests for households can also be called unsustainable (108% of its productivity), while the Asia-Pacific region (89%) also gets relatively close.

The household consumption footprint is higher than the theoretical domestic sustainable productivity (100% NAI) in Brazil (132% of productivity), Africa (137%), the Middle East (900%), India (568%) and China (102%). On the other side are the EU, USA, Russia and America, with sustainable productivity for global markets and domestic household timber footprints which could be easily fully sourced domestically.

Comparison at country level (Appendix Table C-3) indicates that among the largest consumers (>0.58 m^3/cap average), only Brazil's households consume more timber than the estimated domestic sustainable productivity (100% NAI). No EU country has unsustainable household timber production, while outside the EU South-Africa and Mexico have unsustainable production. It is overall clear that at 2011 household consumption, and likely also total consumption levels, the EU could sustainably produce all timber embodied in its consumption. Yet, Belgian, Dutch and Cypriot households do consume more timber than they can sustainably produce. Outside the EU, this is also seen for the UK, China and Japan. At 80% NAI, household consumption in Greece, Ireland, Italy and Turkey can also not be met domestically in a sustainable manner.

However, it must be kept in mind that these comparisons only provide a rough indication of sustainability. The FLAWS and NAI are both subject to uncertainty (O'Brien, 2016): particularly European countries are well-documented, with limited FLAWS ranges (Figure 24) and NAI values available in different reports (e.g. FAO, 2015; Forest Europe, 2015). Furthermore, forestry plantations are not always included in the NAI value. The average plantation NAI is 15.04 m^3/ha versus 2.09 m^3/ha in (semi-)natural forests (O'Brien, 2016). Comparing realistically available forestland to timber productivity, production in Africa, India and the Middle East is seen as unsustainable, while sufficient forest area is available. Shares of plantations (FAO, 2020b) likely explain at least part of this discrepancy for India (9.7 Mha plantations) and the Middle East (e.g. Iran, 0.9 Mha plantations). African plantations (7.6 Mha) are however small relative to its total production. At 11.2 Mha, Brazil has large plantations, but it is also the only of 49 regions with both unsustainable domestic timber production and forest use larger than realistically available.

Determining a sustainable share of NAI harvests is overall hard, but will be necessary to properly monitor the bioeconomy. As such, this indicator requires more research as it depends on forest characteristics and management types in different areas of the world (O'Brien & Bringezu, 2017).

On a global scale, particularly Africa along with South America were found to continue losing forests, with respectively 3.94 Mha and 2.6 Mha lost over the period 2010-2020 (FAO & UNEP, 2020). China and India are among the largest net gainers in forests in the period 2010-2020 (FAO, 2020b), further stressing sustainability trends can be difficult to estimate, and change quickly particularly through afforestation efforts. Especially household consumption exceeding sustainable levels in Africa, Brazil and the America regions can be considered the most worrisome as these regions are home to large forest areas.

5.2.2. Household forest footprints and equitable consumption

A select number of consumers dominate global forest footprints. The top 5 timber consumers RoW Africa, China, USA, Brazil and Russia represent 57% of the global household timber footprint (Figure 6). Russia, RoW Africa, RoW America, China and Brazil meanwhile represent 64% of the global household forestland footprint (Figure 11). Timber harvests in Brazil, RoW Africa and China were considered to be unsustainable in the previous section. In South America, Brazil is represents 1.5 Mha or 58% of the 2.6 Mha forest loss in the period 2010-2020, although losses are recently decreasing (FAO, 2020b). In Africa, the 3.94 Mha forest loss over the same period is still increasing in all regions, with the largest losses in the Democratic Republic of Congo (-1.1 Mha), Angola (-0.56 Mha) and the United Republic of Tanzania (-0.42 Mha) (FAO, 2020b).

With the exception of Russia's forestland consumption, regional per capita footprints in general look very different (Figure 14, Figure 18), and instead show mainly higher income countries as top consumers. India, Indonesia, South-Africa, RoW Middle East and RoW Africa all have smaller than average forest footprints. The largest footprints, found in Scandinavian households, consume 3-4 times more timber and 3-5 times more forestland than RoW Africa and 19-24 times more timber or 32-48 times more forestland than the smallest household consumers in India. This trend indicates an association to income, and lifestyle and resource availability.

Earlier studies showed the relation of footprint size to income level (Ivanova et al., 2016; Tukker et al., 2014; Weinzettel et al., 2013; Wiedmann et al., 2015). Although still present for forest footprints (Figure 20), especially for timber (Figure 20), the link is weaker with regions such as Russia and Brazil having high per capita footprints and RoW Africa with the largest total household timber footprint. Lifestyle as such is likely also a major factor.

Large footprints in Scandinavia could for example be related to a traditionally high wood use for housing (Huuhka & Lahdensivu, 2016; Sandberg et al., 2014). Large total land footprints in Scandinavia were also found in other studies (Lugschitz et al., 2011; Weinzettel et al., 2013), mainly caused by forestry products. In Russia, too, construction and manufactured products are major wood consumers, besides paper production (Liang et al., 2016). This is in contrast with traditional biomass use seen in lower income countries where fuelwood and agricultural wastes traditionally provide energy to satisfy basic needs such as cooking and heating for more than 2 billion people (Bonjour et al., 2013; FAO, 2010b). It is also used as energy source for metal, brick, food and other industries, including the forestry industry which also burns industrial roundwood (FAO, 2007, 2010b; GIZ, 2015). In general this tendency towards use in lower income countries was found both for overall biomass (Figure 3) and fuelwood (Figure 15) consumption.

A third major factor is that the size of timber and forestland footprints seems to be strongly related to forest resource availability. This is in line with previous research relating high land-based footprints to higher resource availability (Ivanova et al., 2016; Weinzettel et al., 2013). Yet, such high availability does not mean displacements are decreased (Weinzettel et al., 2013).

Large displacements also occurred even for the largest consumers of embodied timber and forestland. Although limited resources can also be a driver, higher income levels favor increased displacements of forest footprints. Brazil and Russia for example had large forest footprints, but low displacements. This fits into the overall trend of developed countries displacing impacts, often towards developing regions (Wiedmann & Lenzen, 2018). While such increase is visible for the USA, the EU overall did not follow (-44% for timber displacement, -40% for forestland) and likely somewhat skews individual displacement figures as these include internal EU trade. Yet, despite decreases, 27% of its timber footprints are still displaced with a large amount (9%) to Africa, besides China, Brazil and America (C-/S-America without Brazil), and hence regions with risks for sustainability. The reason for such dependency on African timber is appears to be linked to colonial history (Meyfroidt & Lambin, 2011). On a global scale, increasing exports of Brazil, and especially RoW Asia-Pacific and China should be monitored, as the calculations showed timber production for household consumption to be close to 100% NAI productivity.

Trends in displacements are also worrisome because while Africa and South America lost forests, Europe and Asia have gained forest area since the 1990s (FAO & UNEP, 2020). Over time, so-called forest transitions occurred signalling the change from net forest area loss to expansion (Meyfroidt & Lambin, 2011). International displacements of timber production reinforced by globalization and lower prices can reduce reforestation efforts in the importing country (Meyfroidt & Lambin, 2011). Yet, forest transitions have also been linked to increasing displacements (Kastner et al., 2011; Meyfroidt et al., 2010), with displacement of associated deforestation possibly even enabling such transitions (Pendrill, Persson, Godar, & Kastner, 2019).

Within the context of limited resources and planetary boundaries, the question then arises what would be fair shares for per capita global footprints (Häyhä et al., 2016; Hoekstra & Wiedmann, 2014). In this regard, O'Brien (2016) argues for fair access to forests and their products to meet needs and enhance development, where a sustainable reference value can be used to assess fair distribution and disproportionate consumption. The results show that 36 out of 49 regions consume more than the 0.31 m^3/cap global consumption, which at 100% NAI is close to the limit when considering this only accounts for 54% of timber consumption. The 0.58 m^3/cap global average household footprint is in fact already close to a 100% use of the NAI, and overshoots more conservative NAI shares. Higher-income regions such as Scandinavia, Canada and Austria consume more than 1 m^3/cap. Concurrently, RoW Africa's (0.48 m^3/cap) and Brazil's (0.88 m^3/cap) footprints are also high relative to the 0.31 m^3/cap global value. This finding complicates the concept of fair distribution.

The energy need in lower income countries, which is expected to further increase (GIZ, 2015), is of relevance to achieving SDG7 regarding access to affordable, reliable, sustainable and modern energy (UN General Assembly, 2015). Without such access, it can be argued that a fair distribution entails that lower income regions in need of energy should be allowed to consume more forest products. As income level was found to affect but not fully predict footprint sizes, the use of wood in high-income countries is likely linked to choice rather than need. In this sense, and because of the globally increasing industrial roundwood consumption, it cannot simply be demanded that low-income countries reduce fuelwood use.

5.2.3. Sustainable wood production

With the importance of achieving sustainable development goals and concurrent striving towards a stronger EU bioeconomy, the question is what role wood can play. The EU demand has been within the range of sustainable supply (O'Brien & Bringezu, 2017). However, estimates expect total woody biomass consumption to strongly increase: from 458 Mm^3 to 620 Mm^3 between 2010 and 2030 for material use to a more than doubling from 346 Mm^3 to 752 Mm^3 for energy use driven by Renewable Energy Directive goals (Mantau et al., 2010). Under existing conditions and with sustainable productivity in mind, such expansion seems difficult to achieve.

Similar to earlier footprint studies mentioning productivity differences for EU and Swiss footprints (Bringezu et al., 2012; O'Brien & Bringezu, 2018), the forestland-timber ratio varied strongly across nations, ranging from Russia at 1.95 ha/m^3 to the majority (32 regions) consuming less than 0.5 ha/m^3. Factors such as location, forest type and management affect the productivity, which can differ over time (O'Brien, 2016).

SDG15 is directly related to sustainable forest management, in terms of both socio-economic and environmental dimensions (FAO & UNEP, 2020). Different forest management approaches affect factors such as timber productivity, biodiversity, carbon storage and sequestration and other ecosystem services (Chaudhary et al., 2016; Duncker et al., 2012). This is also why sustainable management in SDG15 not only benefits biodiversity, but has furthermore positive links to SDG1 (income to fight poverty), SDG2 (wild food), SDG3 (medicinal plants), SDG6 (fresh water) and SDG13 (carbon capture and storage) (Baumgartner, 2019).

The choice for specific forest management system to meet timber demand can ultimately be linked to the land-sparing and land-sharing debate (Edwards et al., 2014). Land-sparing would focus on intensive forestry while protecting large forest areas, which could help meeting timber demands with less harm to biodiversity than land-sharing mixing both functions (Edwards et al., 2014). As such, a suggestion has been to focus on intensively managed tree plantations to increase roundwood production and facilitate forest transitions (Meyfroidt & Lambin, 2011). Managed afforestation could in fact be particularly interesting on degraded abandoned agricultural lands (Paul & Knoke, 2015).

Yet, expanding forestry plantations is challenging in a competition for land, particularly from agriculture (Meyfroidt & Lambin, 2011; Payn et al., 2015). Besides agricultural pressures, plantations also risk being established on existing natural forests (Barua et al., 2014; Meyfroidt & Lambin, 2011). Still, additional plantations would likely be required to avoid increasing pressures on natural forests, either in cleared natural forests or on cropland with displacement of agricultural deforestation elsewhere (Mishra et al., 2021). Plantations are the timber management systems with the largest impacts on species richness relative to natural forests at an average loss of 40% (Chaudhary et al., 2016). Yet, their productivity can be an argument within the land-sparing/sharing debate (Mishra et al., 2021). Considering biodiversity and various ecosystem services provided by intact forests are reduced by their degradation (Watson et al., 2018), sparing more natural forests could be preferable in a context of increasing timber demand.

For the EU, the problem is that the above-mentioned large demand increases are difficult to achieve even through wide-ranging productivity, land management, logistical and other measures (Mantau et al., 2010). At the global level, limited European productivity improvements furthermore increase dependency on imports (UNEP, 2015) causing global displacement of impacts. Considering forests globally are under pressure, it will be key to ensure the bioeconomy does not surpass the sustainability of global production systems.

For developed countries, strong forest governance can support sustainability of a bioeconomy based on wood increment levels (Szulecka, 2019). Yet, such binding criteria for sustainability are missing at EU level, while imports are mainly judged regarding a difficult to enforce legality of harvesting (Szulecka, 2019). While an option under consideration for the EU is to require imports to be at the producer-country's standards, this still leaves room for both legal deforestation and legalized illegal deforestation (Reis et al., 2021). A sustainable bioeconomy would as such likely benefit from enforcing and monitoring specific EU criteria for own production and imports. A global sustainable bioeconomy would additionally require strong multilateralism.

5.2.4. Reducing products' impacts on forests

Compared to other household footprints having mobility, shelter and food as main contributors (Ivanova et al., 2016), the forest footprints show a different pattern. Shelter dominates the global footprints, particularly through products of forestry (50% timber footprint, 56% forestland footprint), while manufactured products are second in importance. Instead of 46% of global household land use resulting from food (Ivanova et al., 2016), the lower importance of agriculture means only 11% of the timber and 10% of the forestland footprints result from food. Yet, it should be remembered that especially in tropical areas, agriculture is a major deforestation driver (Pendrill, Persson, Godar, & Kastner, 2019), while forestry activities often entail regrowth (Curtis et al., 2018).

With the current dominance of fuelwood in the household footprints, the importance of bioenergy in the bioeconomy (European Commission, 2018), future projections (Mantau et al., 2010) and its role in climate change mitigation (IEA, 2017; Rogelj et al., 2018), the discussion on reducing impacts on forests is likely to be one centered around bioenergy. Products of forestry dominated the household forest footprints with a 60% of fuelwood share. A share of industrial roundwood is also burned, particularly in the forestry sector (FAO, 2007). At the same time, estimating the total wood fuel consumption and associated deforestation can be difficult as it can have various origins and range from individual use to complex supply chains (Bailis et al., 2017).

In lower-income countries, traditional biomass use, while flourishing, is inefficient and unsustainably managed (Szulecka, 2019). Compared to developing countries' efficiencies of 2-20%, industrialized countries can reach as high as 90% (Rosillo-Calle, 2016). This inefficiency also drives fuelwood demands (UNECE & FAO, 2011). As such, modernization of biomass use ranging from improved cooking stoves to combined heat and power generation, is a key issue to improve sustainability in developing countries (Li et al., 2021; Rosillo-Calle, 2016).

However, as industrial roundwood is more important in high-income regions and increasing on a global scale, it is unfair and risky to only focus on developing countries' fuelwood consumption. It could be recommended to substitute wood for mineral products, but the material footprint is also of relevance for sustainable resource management (SDG12), and has continued increasing (Lenzen et al., 2022). As such, a particular opportunity for reducing impacts on forests exists in wood cascading: efficiently recovering wood and utilizing residues, either for material use or energy in a single additional stage or multiple stages (Vis et al., 2016, p. i). Considering wood and processed wood products contributed the most to the footprints, cascading presents an important opportunity for reducing forest footprints.

Multiple studies have found that optimized cascades can reduce the need for primary wood harvests (Höglmeier et al., 2015; Risse et al., 2017; Taskhiri et al., 2019), thus reducing impacts on global forests. Longer cascades with first high-quality material uses, and ending with energy recovery are preferable and could furthermore reduce impacts through carbon storage and fossil fuel displacement (Faraca et al., 2019; Mehr et al., 2018; Niu et al., 2021). However, this should still overcome the current situation in which energy use competes with material use, as it is for example incentivized in renewable energy legislation (Vis et al., 2016).

Besides solid wood cascades, paper recycling is also relevant. The forest footprint of paper and its intensity was found to be relatively high at EU scale, contributing about 6% to the timber and 5% to the forestland footprint. European paper recycling is currently already at 74% in 2020 (EPRC, 2021). However, contrary to recovery rates, the potential for increasing utilization of recovered paper can be limited as paper types can have varying requirements (Grossmann et al., 2014). As such, maximizing use of recycled products and avoiding waste will be key to minimize wood consumption for paper products.

5.3. Limitations and reliability of the results

Even though EXIOBASE offers comparatively good sectoral detail, the aggregation of products and countries makes interpretation of household impacts more difficult. The limitations are generally linked to the MRIO method (as discussed in the literature review) and the EXIOBASE data.

Especially at scale of total timber and forestland consumption, RoW regions were important consumers and producers. One study (Zhang et al., 2020) earlier indicated the Democratic Republic of Congo as a major timber consumer, and regions such as Ghana and Ethiopia as major exporters. Extremely large differences in forestland footprints found by Bjelle et al. (2020) (e.g. Finland – 6.81 ha/cap vs Yemen – 0.015 ha/cap) similarly indicates more country detail will provide additional information on per capita footprints. This could further fuel the fairness debate regarding footprints (Hoekstra & Wiedmann, 2014). RoW regions possibly also oversimplify the link between income and fuelwood consumption. Although linked to income, fuelwood is not just for the poor: when not needed for basic energy needs, it could be used for stacking to diversify energy sources, or it could be used for lifestyle reasons such as tradition (van der Kroon et al., 2013). This causes in general for results to be unreliable when making links to income levels.

This is the case for all product groups, especially products of forestry dominating the forest footprints as an aggregated group of little processed roundwood and fuelwood products. Such high contribution to total household footprints would require better insight into the precise products, especially for informing policy regarding household consumption. Such detail is however not present in EXIOBASE. Such detail was also not provided by the recent FABIO database (Bruckner et al., 2019) focusing on biomass trade, nor is it provided for forestry products (FAOSTAT, 2022b). Unless product detail can be increased, the suitability of MRIO for forest footprints will be higher for determining the total embodied impacts which are difficult to estimate through ew-MFA. Similarly, if such detailed product data to inform households is unavailable, the focus should likely be on total consumption to fully capture the bioeconomy, while still distinguishing between consumption groups.

Comparison of the results is difficult as there are no similar household forest footprint studies. Transformations to the data, whether to add trade detail or aggregate in product groups or regions were checked by summing the results, which always had to be equal to the total. When not possible, manual checks were performed as well to ensure correct coding. Despite careful handling of data, uncertainties in the data will still remain. This is for example seen when comparing the results from EXIOBASE 3 to household footprints of Ivanova et al. (2016) using EXIOBASE 2. The material footprint in 2007 was found to be slightly lower at 29.8 Gton versus 32.3 Gton while for land it was 8419 Mha versus 6500 Mha. Different data sources, data updates and varying assumptions are all factors that can cause uncertainties.

Comparison to the 3797 Mm^3 in 2015 found by Zhang et al. (2020) suggests an overestimation of the total timber footprint (3966 Mm^3). It is also possible to compare to FAOSTAT data, as this formed the source for EXIOBASE roundwood data. The total 3966 Mm^3 versus the FAOSTAT (2022a) 3671 Mm^3 for 2011 indicates an overestimation of about 8%. Production results for separate countries showed both slight over- and underestimations compared to the recent FAOSTAT data. This is however likely linked to FAOSTAT forestry data updates over time, compared to the older FAOSTAT data in EXIOBASE. This is a limitation of this research which could be overcome by creating updated timber extensions in further research.

The EXIOBASE method for determining productive forestland (Stadler et al., 2018b) also comes with uncertainties. The data is initially from a UN map of forest cover in 2000. Since 2000, millions of hectares have been annually lost in South America and Africa, while Asia and Europe made large gains (FAO, 2020b). This means forestland data in EXIOBASE could be rather outdated by now. Used forestland and marginal forestland shares in the forest area were also kept constant, while unused forest area in the data constantly decreased. These assumptions add major uncertainty to forestland footprints, particularly for time series results and comparisons to 1995. Changes in forestland will hence be driven by changes of consumption in the economy.

Existing literature (e.g. de Laurentiis et al., 2022; Fischer et al., 2017; O'Brien & Bringezu, 2018) focuses on a 'sustainable yield approach' where roundwood production data are multiplied by the net annual increment (NAI) under the assumption of sustainable management at 100% NAI harvests. However, available NAI data (e.g. FAO, 2015; Forest Europe, 2015) mainly covers Europe and high-income regions. Other regions require relying on (continental) averages, while relatively wide ranges indicate uncertainty, further influenced by large differences between (semi-)natural forests and plantations (O'Brien, 2016).

For the EU, the 89.9 Mha household forestland is lower than the total 122 Mha in 2011 found by O'Brien et al. (2018) or 107.7 Mha for 2018 found by de Laurentiis et al. (2022). However, considering the presented results refer to the household footprint (54% of total), this is on a rather high side, which is likely related to the ew-MFA method in other studies not being able to capture all embodied impacts. Yet, a study combining EXIOBASE with the sustainable yield approach (Fischer et al., 2017) estimated the EU forestland requirement at about 230 Mha, suggesting a possibly large overestimation through the sustainable yield method.

Other methods using FAOSTAT productive forestland data were also earlier explored (de Laurentiis et al., 2022; Fischer et al., 2017; Stadler et al., 2018b), but deemed unreliable due to varying country definitions of forest management and lack of reporting in some countries. Using Global Forest Resources Assessment data, Yu et al. (2013) furthermore found the same major import regions as in this thesis, but much larger displacements of total forestland, e.g. 10 times higher for Russia. For future forestland accounting, a direct comparison of existing methods and review of possible improvements could benefit the monitoring of global use of forestland.

Another major limitation of the study is its limited time-series of 1995-2011. Although the trend over time is comparable to wood removals (FAO, 2020b) being relatively stable around 3500 Mm^3 from 1990 to 2010, renewed growth was seen afterwards. One global study (Zhang et al., 2020) noted a continuous growth trend. Now-casts in EXIOBASE 3.8 beyond 2011 which were initially considered but deemed unreliable for this research, also indicated a further growth.

Monitoring of the bioeconomy in a timely manner is important to adequately ensure sustainability. A recent study associated the bioeconomy plans to abrupt European harvest increases since 2015 (Ceccherini et al., 2020). Although uncertainties exist regarding data, it also stresses the need to evaluate available data to inform EU policy and enhance the collective European effort for multidisciplinary data collection on European ecosystems (Palahí et al., 2021). The household forest footprints provide an indication of pressures, but a growing bioeconomy requires ongoing efforts for more timely monitoring.

Lastly, interpretation of the forest footprints cannot directly be translated to forest area loss, deforestation and biodiversity impacts. For studying such impacts, a specific focus (e.g. Hoang & Kanemoto, 2021; Moran & Kanemoto, 2017; Pendrill, Persson, Godar, & Kastner, 2019) will provide more information. However, the presented footprint study is specifically important for assessing the sustainability of the bioeconomy, which should continue to be monitored in the future.

6. Conclusion

Household consumption was responsible for 54% of the global timber and 60% of the global forestland footprints in 2011. The household timber footprint was 2158 Mm^3 in 2011, a decrease of 4% relative to 1995. The household forestland footprint decreased by 8% to 1327 Mha in 2011. Such decreases are not in line with the increasing biomass and mineral footprints, although it is unlikely that much space is left for further sustainable growth. At the same time, it is important to be cautious, as almost exlusively fuelwood consumption for shelter has reduced the footprints and industrial roundwood use is increasing globally across product categories.

The top 5 timber consumers RoW Africa, China, USA, Brazil and Russia represent 57% of the global household timber footprint. Russia, RoW Africa, RoW America, China and Brazil represent 64% of the global household forestland footprint, with varying contributions indicating major productivity differences. At per capita level, these pictures are very different, with 15 out 49 regions exceeding the timber footprint average (0.58 m^3/cap) and 13 regions exceeding the average forestland footprint (0.3 ha/cap). Differences are associated to income, resource availability and lifestyles. This is seen in the largest footprints, with the exception of forestland in Russia, being found in high-income countries (e.g. Scandinavia, Canada). As many high-income countries have large per capita footprints, lifestyle appear to increase forest resource consumption in those countries with sufficient productive forest area. This is also the case in regions with lower incomes, such as Africa and Brazil, where traditional fuelwood use plays an important role and dominates the footprints, in this case often to cover basic energy needs.

Satisfying basic needs makes it even more important to harvest timber sustainably. However, 36 out of 49 regions exceed the global 0.31 m^3/cap, which could be seen as a sustainable reference value for household consumption at 100% NAI, considering this represents only 54% of the total timber consumption. Particularly harvests in Africa, which is a large timber exporter, and Brazil appear to be unsustainable, although risks also exist for major exporters such as China and the Asia-Pacific region. This stresses the importance of monitoring the bioeconomy and applying criteria for sustainability. This should also cover foreign timber harvesting, as increasing displacements are adding to the problem in achieving sustainable forest resource use.

Dependency on displacements increased on average by 10% to 48% for timber and 52% for forestland. Many regions have larger displacement dependencies on forestland than timber, meaning outsourcing to less productive regions is common. Net exporters of forest footprints are generally abundant in forest (e.g. Canada, Sweden, RoW Africa, Russia), while net importers are industrialized or emerging economies (e.g. Japan, USA, Germany, India, China). At 25% of the global household timber footprint, the African continent produces the most timber. Russia alone represents 27% of the productive forestland for household consumption. The EU displaces major parts of its forest footprint to these countries, with Africa alone representing 9% of its timber footprint, along major imports of embodied timber and forestland from China, non-EU Europe and Latin-America. Despite large decreases of displacement (-44% total household timber, -40% for forestland) likely resulting from increased internal trade, such displacements still add pressure on global forests.

Comparing both forest footprints, the efficiency is the worst for Russia at 1.95 ha/m^3, while the majority (32 regions) even used less than 0.5 ha/m^3. This shows how a different management style can strongly influence the footprints. Sustainable forest management practices are key to guarantee sustainability, in which afforestation via tree plantations on low-quality soils could provide opportunities. However, in the EU, opportunities for productivity improvement are limited, which would again require more displacements. Although the footprint intensity decreased for almost all regions and products, the consumption of primary wood in products likely still provides room for improvement.

Shelter dominates forest footprints (average resp. 49% of timber and 48% of forestland footprints), especially in low- to mid-income countries. Particularly manufactured products (both 15% average) and services (both 11% average) increase with higher income, while clothing is the least important category (both 4% average). The top 10 products represent 79% of the household timber and 82% of the household forestland footprints. They are dominated by little processed wood, furniture, paper and other wood products, particularly through products of forestry which mainly consists of fuelwood on a global scale and industrial roundwood in the EU. As wood is needed for energy in developing countries, increasing its efficient use through modernizing energy appliances provides chances. Yet, on a global scale and in the context of limited potential for growth of the woody bioeconomy, increasing cascading material uses of wood in multiple steps, and ending with energy use, seems like a preferable pathway for a sustainable bioeconomy.

7. Recommendations

Based on the presented thesis research, several recommendations can be made for further research and policy:

Work on a framework for monitoring of the woody bioeconomy based on concrete criteria. As opportunities for further growth appear to be limited, it is important to monitor the bioeconomy to ensure that forests are not overharvested domestically nor abroad. This requires a concrete framework for analyzing consumption and production, and specific sustainability criteria. A clear drawback of EXIOBASE is currently its limited coverage in time and regions. To enable timely monitoring, it is important to invest in further development and updating of the chosen method.

Review the methods for accounting for forestland embodied in consumption. Understanding forestland footprints is important as it expresses the extent of disturbed forest area and potential biodiversity impacts. However, accounting for forestland is difficult due to a lack of reported data, while the sustainable yield method requires assumptions increasing uncertainty. Using the extensions of EXIOBASE 3, this thesis made use of productive forestland data that was determined through maps of intact and used forests. Analyzing this method against the sustainable yield method, FAOSTAT data and other information could provide insights in the reliability of this method. Doing so, it can also be attempted to further improve on the forestland footprint indicator.

Improve the reliability of a sustainability indicator for timber harvesting. Although the presented forest footprints provide many insights into the global impacts on forests embodied in household consumption, some reference value for sustainable consumption should be provided. This is important for ensuring sustainability of timber harvests, but also for working towards fair reference values for global consumption in the context of limited resources. However, NAI and FLAWS ranges are still very uncertain for most regions other than Europe, and the sustainable share of NAI harvests is likely somewhere below 100%. Thus, more research is needed for providing more accurate global timber productivity values, as well as for providing safe NAI shares for timber harvesting, taking into account global differences in forests and their management.

Analyze forest footprints for disaggregated regions. Multiple links were found between the timber and forestland footprints and income levels. However, low-income countries are generally aggregated into one of the five Rest of World regions, which are additionally also major sourcing regions for wood. This makes analysis regarding sourcing country and associations to income level less precise. As such, these links could benefit from analysis through other MRIO databases, or from building upon the disaggregated EXIOBASE-database presented by Bjelle et al. (2020).

Improve the global efficiency of timber consumption in a fair manner. Fuelwood is an important part of the household forest footprints, particularly in developing countries where it is a vital energy source. Pressures of the bioeconomy on forests can be relieved by investing in modern energy, including appliances, in developing countries. The focus thereby should however be on simultaneously improving development instead of enabling increased consumption elsewhere, as this is not equitable in the face of growing industrial roundwood consumption. Therefore, globally, it is important to increase cascading of industrial roundwood through multiple stages, which as of now is still often limited to burning for energy. Doing so should help to reduce the global pressures on forests, especially in a context of a growing bioeconomy.

Use low quality land as an opportunity for simultaneously improving biodiversity, timber production and overall ecosystem services. In a context of limited land, intensification in the form of plantations becomes an option. As they are much less biodiverse, they should not replace (semi-)natural forests. However, plantations form an interesting option for degraded abandoned land, where they could somewhat reduce the land competition and provide a win-win for increased timber production and biodiversity.

8. Literature

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Appendix A. Global level figures

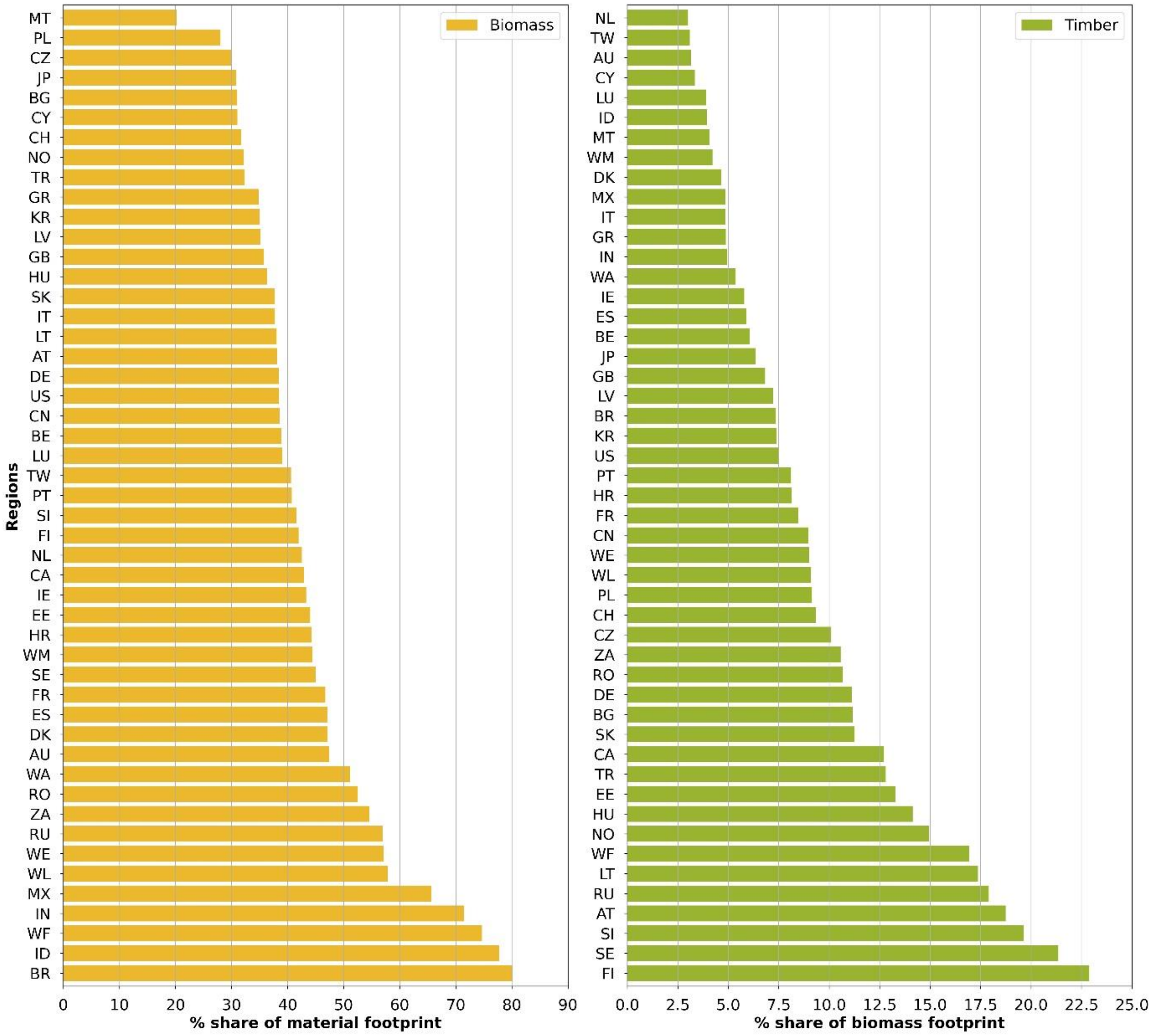

Figure A-1. (a) Regional shares of biomass in the material footprints of household consumption in 2011. (b) Regional shares of timber in the biomass footprints of household consumption in 2011.

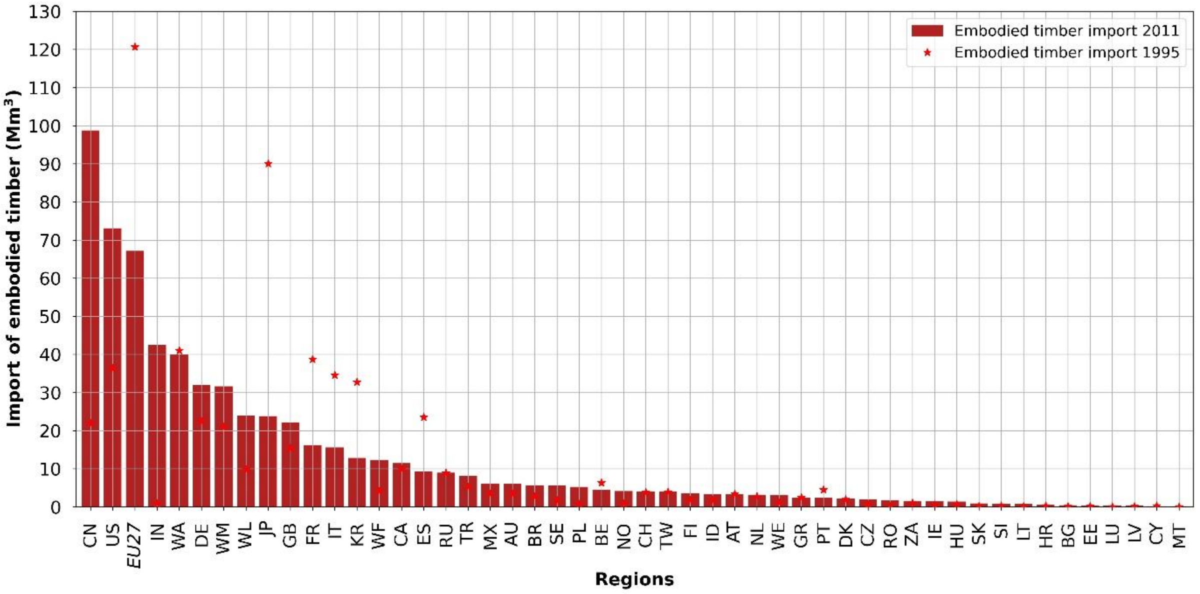

Figure A-2. Imports of embodied timber in million m³ to satisfy household consumption in indicated regions in 2011 compared to 1995.

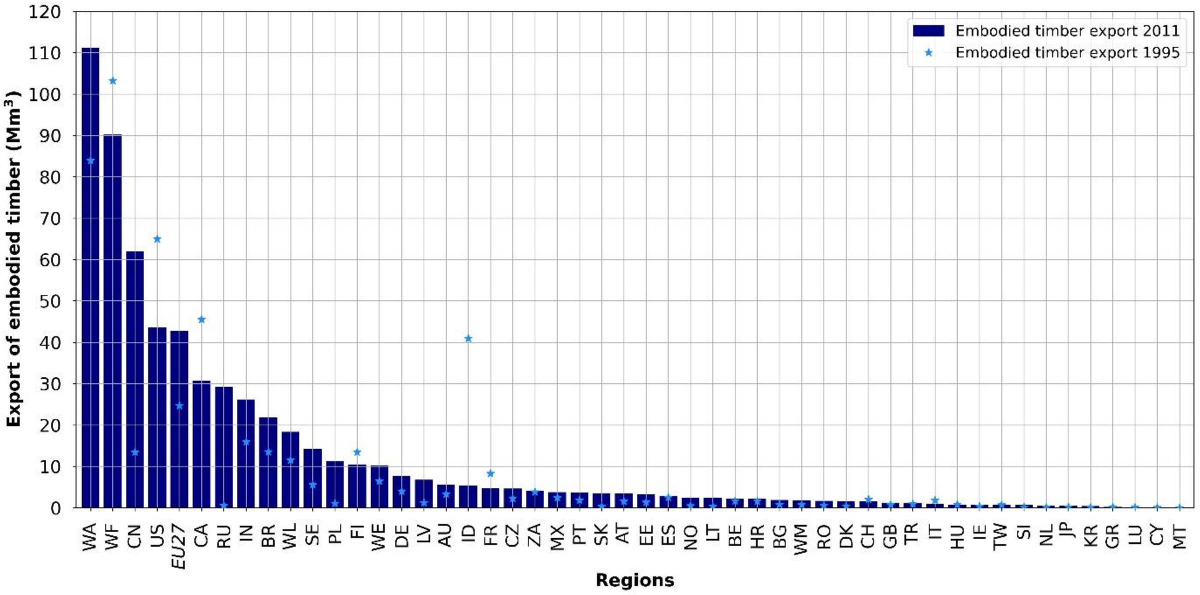

Figure A-3. Exports of embodied timber in million m³ by indicated regions to satisfy foreign household consumption in 2011 compared to 1995.

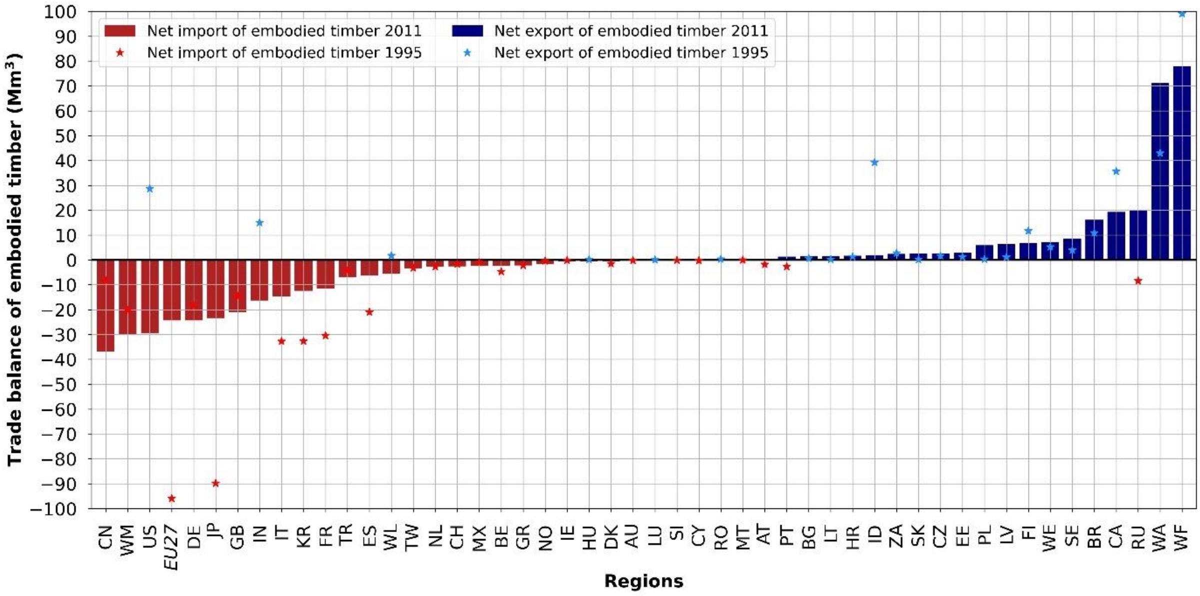

Figure A-4. Trade balance of embodied timber in million m³ by indicated regions to satisfy household consumption in 2011 compared to 1995.

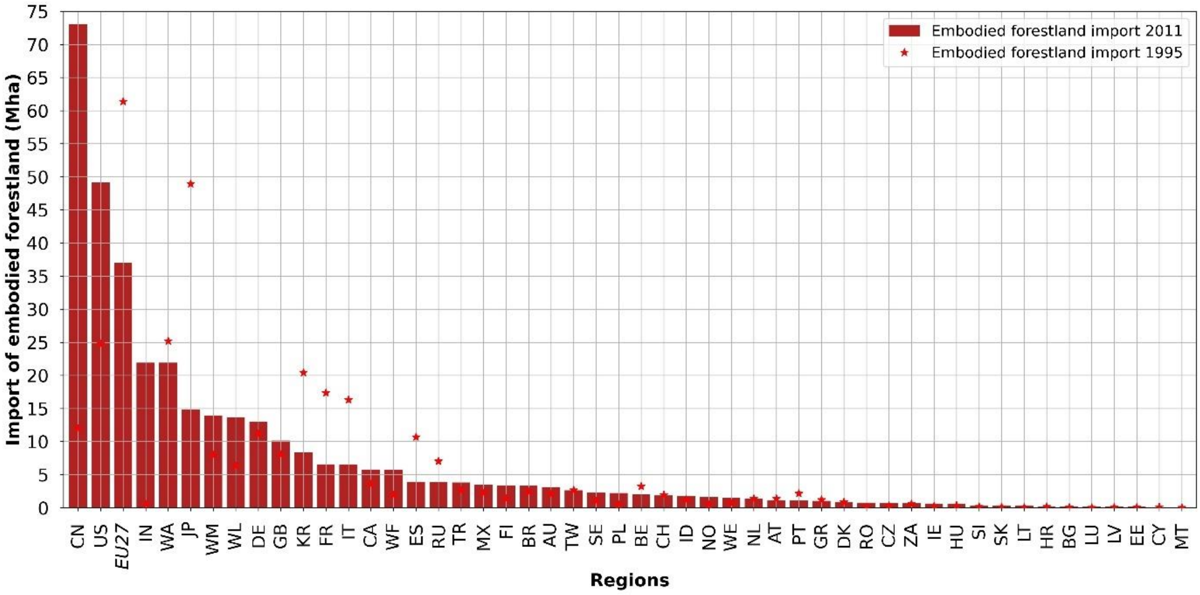

Figure A-5. Imports of embodied forestland in million hectares to satisfy household consumption in indicated regions in 2011 compared to 1995.

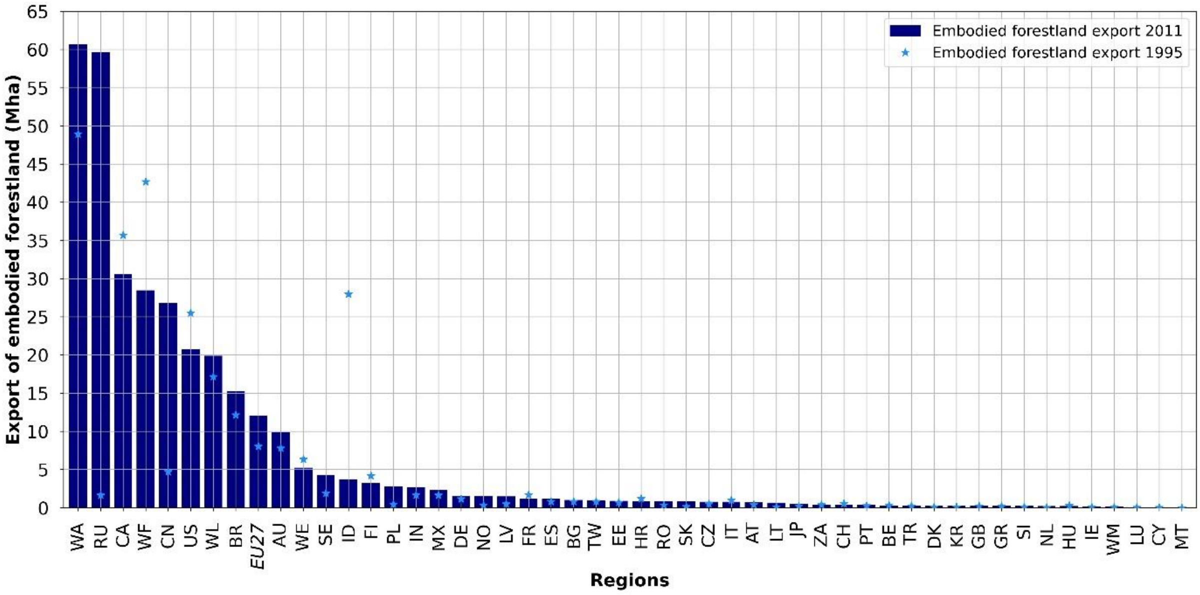

Figure A-6. Exports of embodied forestland in million hectares by indicated regions to satisfy foreign household consumption in 2011 compared to 1995.

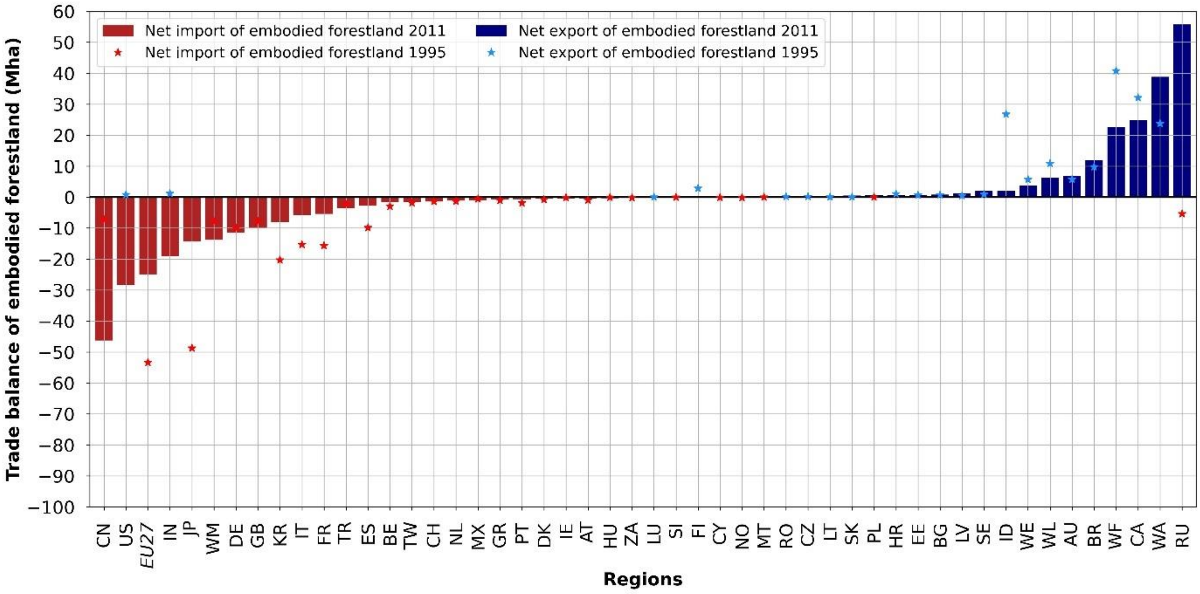

Figure A-7. Trade balance of embodied forestland in million hectares by indicated regions to satisfy household consumption in 2011 compared to 1995.

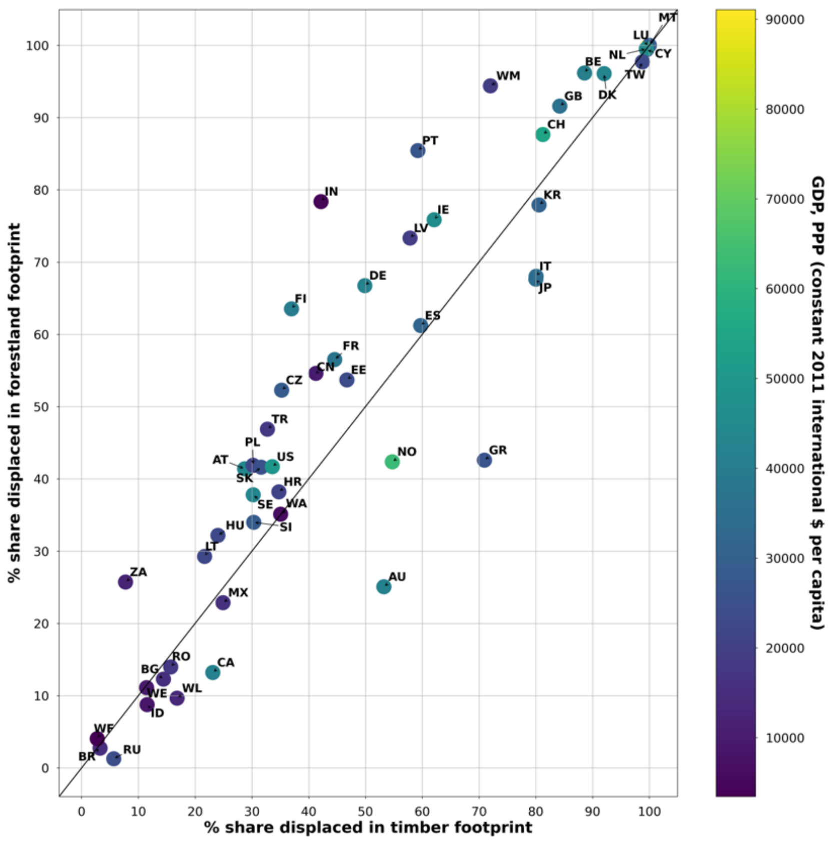

Figure A-8. Shares of displacement in regional timber and forestland footprints of 2011 for all 49 regions, in relation to the income level (GDP PPP constant 2011 international $ per capita).

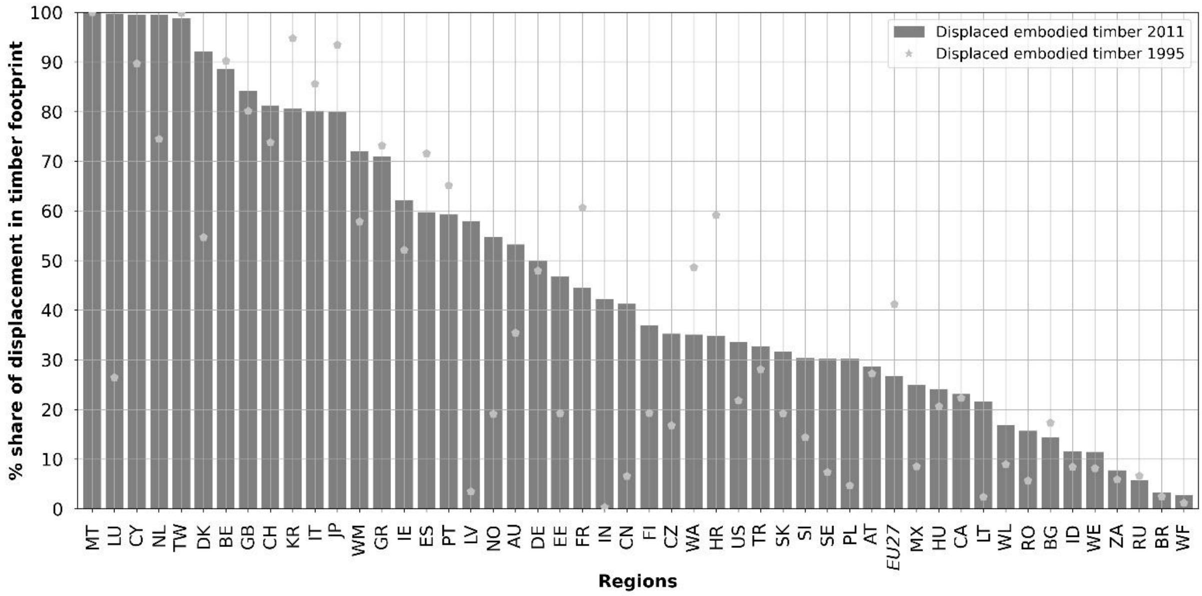

Figure A-9. Shares of timber footprint displaced abroad in 2011.

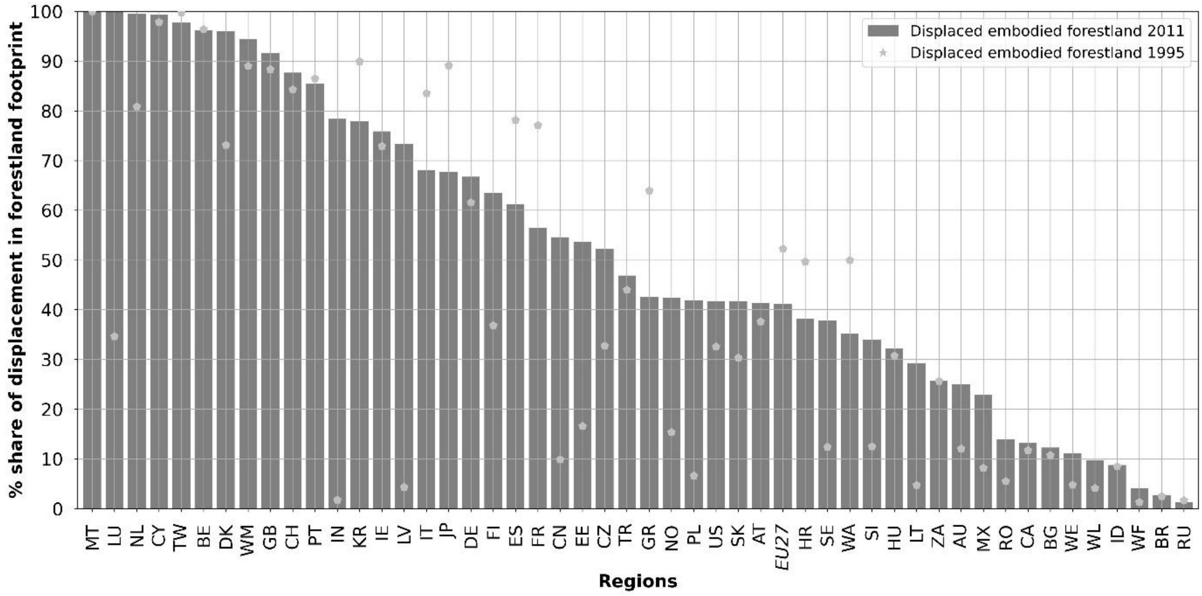

Figure A-10. Shares of forestland footprint displaced abroad in 2011.

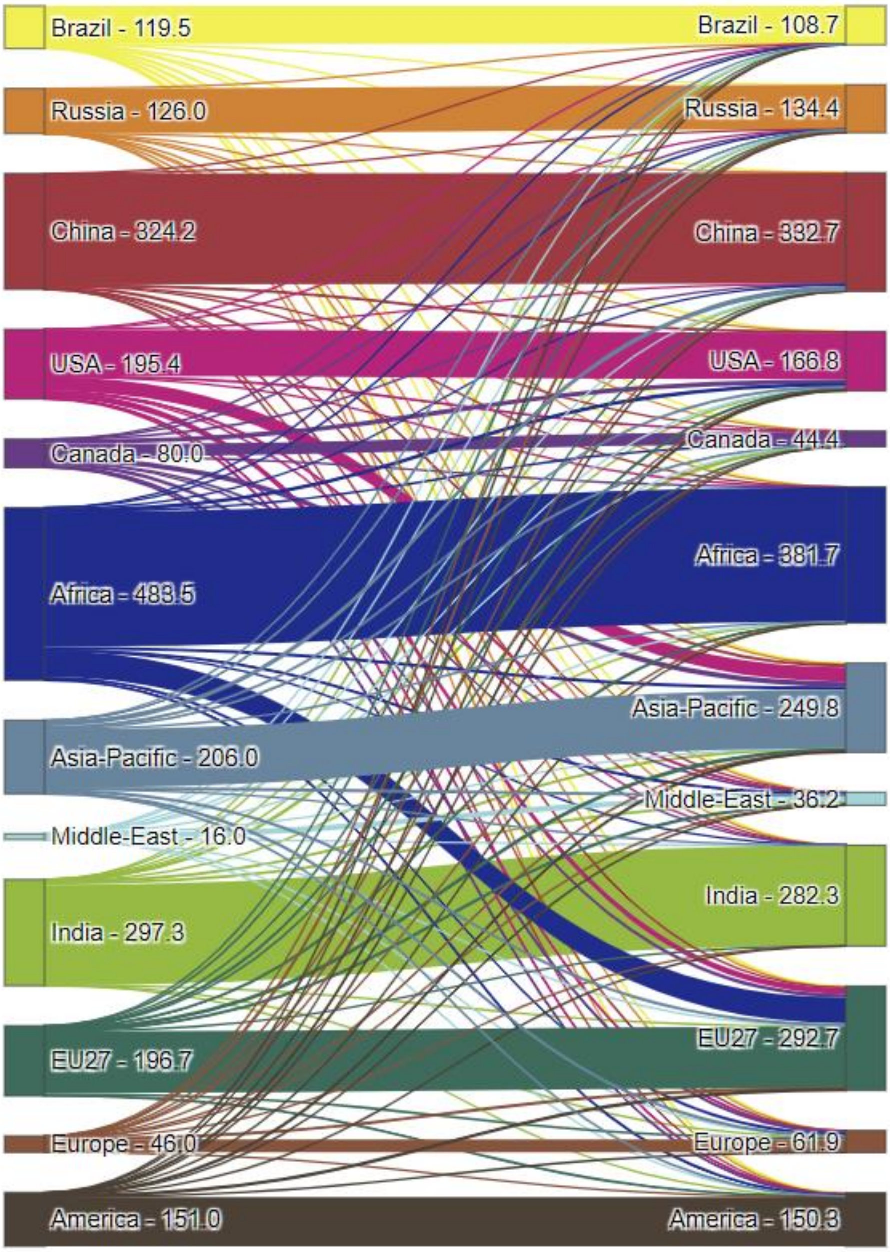

Figure A-11. Trade flows between major sourcing regions (left) and major consumers (right) of embodied timber in 1995, with total values given as Mm³.

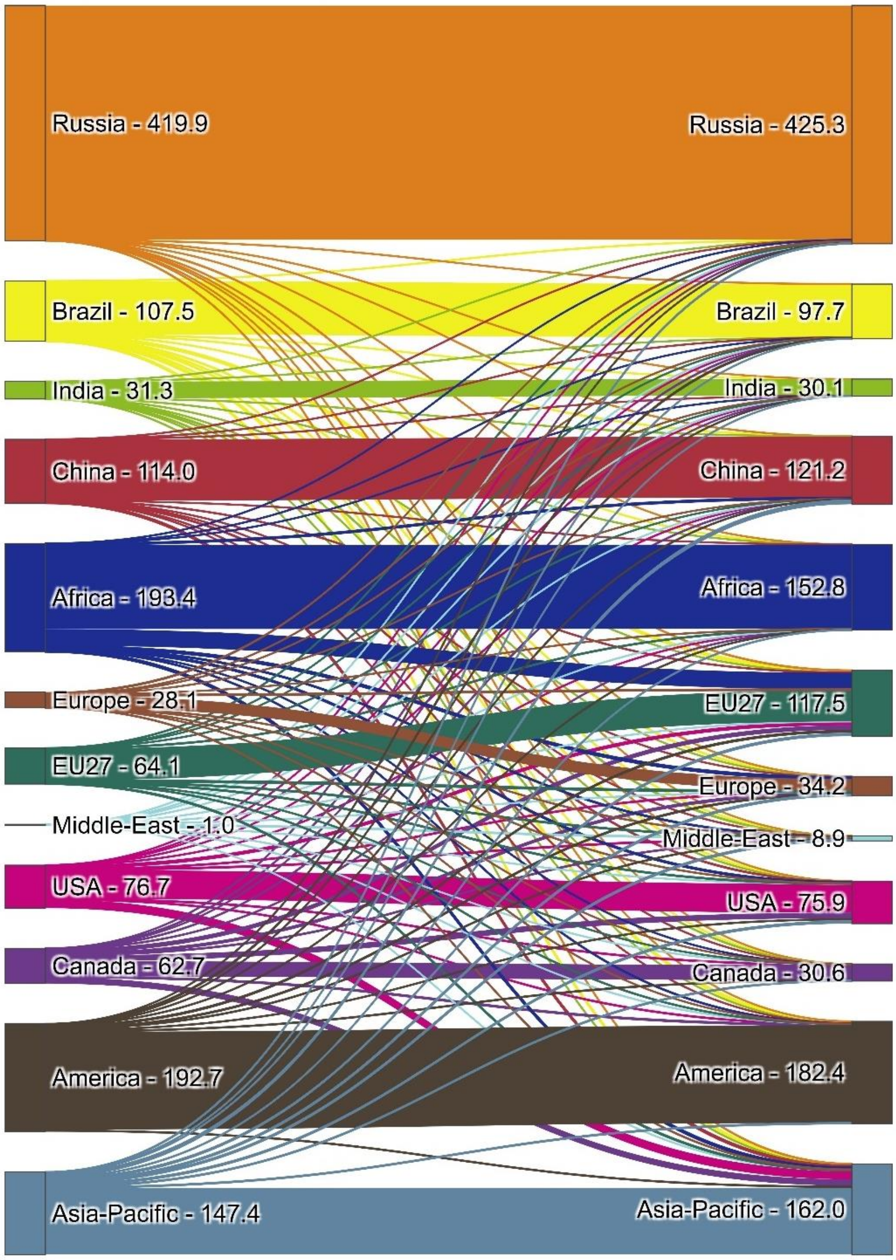

Figure A-12. Trade flows between major sourcing regions (left) and major consumers (right) of embodied forestland in 1995, with total values given as Mha.

Appendix B. Global product footprints

Table B-1. Contributions of the top 20 EXIOBASE product categories to the global timber footprint of household consumption in 2011. All values are given in Mm³.

	Industrial roundwood	Fuelwood	Total	% share in total
Products of forestry, logging and related services	431,5	637,6	1069,1	50%
Paper and paper products	70,5	48,5	119,0	6%
Furniture; other manufactured goods n.e.c.	62,5	47,8	110,3	5%
Food products n.e.c.	47,3	37,5	84,8	4%
Real estate services	45,6	23,7	69,3	3%
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	38,1	31,0	69,1	3%
Health and social work services	36,4	17,6	54,1	3%
Chemicals n.e.c.	21,7	25,8	47,5	2%
Hotel and restaurant services	24,1	18,1	42,2	2%
Wearing apparel; furs	16,4	20,7	37,1	2%
Printed matter and recorded media	16,6	15,0	31,6	1%
Motor vehicles, trailers and semi-trailers	16,4	8,6	25,0	1%
Beverages	13,9	10,2	24,1	1%
Textiles	8,5	12,0	20,5	1%
Tobacco products	6,9	13,2	20,1	1%
Rubber and plastic products	9,0	8,6	17,5	1%
Other services	9,3	7,8	17,1	1%
Dairy products	9,2	5,5	14,7	1%
Fish products	6,2	7,9	14,1	1%
Recreational, cultural and sporting services	7,4	6,5	13,9	1%
Other products (aggregation of remaining 180 products)	136,7	120,6	257,4	12%
TOTAL	1034,2	1124,1	2158,4	

Table B-2. Contributions of the top 20 EXIOBASE product categories to the global forestland footprint of household consumption in 2011. All values are given in Mha.

	Forestland	% share in total
Products of forestry, logging and related services	743,2	56%
Paper and paper products	67,8	5%
Furniture; other manufactured goods n.e.c.	55,8	4%
Food products n.e.c.	48,9	4%
Real estate services	36,7	3%
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	36,1	3%
Health and social work services	28,5	2%
Chemicals n.e.c.	26,6	2%
Hotel and restaurant services	23,3	2%
Wearing apparel; furs	19,1	1%
Printed matter and recorded media	15,7	1%

Beverages	13,7	1%
Motor vehicles, trailers and semi-trailers	12,8	1%
Rubber and plastic products	10,2	1%
Textiles	9,5	1%
Other services	9,3	1%
Dairy products	8,5	1%
Vegetables, fruit, nuts	8,1	1%
Fish products	8,1	1%
Recreational, cultural and sporting services	7,3	1%
Other products (aggregation of 180 other products)	137,4	10%
TOTAL	1326,5	

Table B-3. Top 10 products with largest timber footprint (Mm^3) in the EU27 in 2011.

Product category	**Industrial roundwood**	**Fuelwood**	**Total**	**% share**
Products of forestry, logging and related services	49,8	40,8	90,6	36%
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	14,3	10,5	24,8	10%
Furniture; other manufactured goods n.e.c.	10,6	9,0	19,7	8%
Real estate services	8,3	4,0	12,3	5%
Food products n.e.c.	4,5	5,5	10,0	4%
Paper and paper products	5,2	2,8	7,9	3%
Hotel and restaurant services	3,0	3,8	6,8	3%
Printed matter and recorded media	2,8	2,3	5,0	2%
Wearing apparel; furs	1,4	3,2	4,6	2%
Motor vehicles, trailers and semi-trailers	1,8	2,0	3,8	2%
Other products (aggregated 190 other categories)	32,6	33,4	66,0	26%
TOTAL	134,4	117,3	251,6	

Table B-4. Top 10 products with largest forestland footprint (Mha) in the EU27 in 2011.

	Forestland	**% share**
Products of forestry, logging and related services	28,7	32%
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	7,7	9%
Furniture; other manufactured goods n.e.c.	7,0	8%
Food products n.e.c.	4,2	5%
Real estate services	4,1	5%
Paper and paper products	3,4	4%
Hotel and restaurant services	2,8	3%
Wearing apparel; furs	2,2	2%
Printed matter and recorded media	2,0	2%
Motor vehicles, trailers and semi-trailers	1,5	2%
Other products	26,4	29%
TOTAL	89,9	

Table B-5. Contributions of aggregated product categories to the EU's timber and forestland footprints in 2011 with changes relative to 1995.

	Shelter	Food	Clothing	Mobility	Manufactured products	Services	TOTAL
Industrial roundwood – Coniferous	70.3 Mm^3 (-8%)	11.3 Mm^3 (+14%)	2.2 Mm^3 (+59%)	5.4 Mm^3 (-18%)	18.8 Mm^3 (-12%)	9.7 Mm^3 (-4%)	117.6 Mm^3 (-6%)
Fuelwood – Coniferous	9.5 Mm^3 (+39%)	1.7 Mm^3 (+78%)	0.9 Mm^3 (+351%)	0.8 Mm^3 (+48%)	2.5 Mm^3 (+46%)	1.3 Mm^3 (+53%)	16.8 Mm^3 (+51%)
Industrial roundwood – Non-coniferous	25.6 Mm^3 (-13%)	5.9 Mm^3 (+10%)	2.4 Mm^3 (+138%)	2.6 Mm^3 (-6%)	8.3 Mm^3 (-14%)	4.2 Mm^3 (-2%)	49 Mm^3 (-6%)
Fuelwood – Non-coniferous	34.7 Mm^3 (-31%)	9.9 Mm^3 (-21%)	4.1 Mm^3 (+54%)	4.1 Mm^3 (-34%)	9.1 Mm^3 (-60%)	6.2 Mm^3 (-30%)	68.2 Mm^3 (-34%)
TOTAL timber footprint per category	140.1 Mm^3 (-14%)	28.9 Mm^3 (+0%)	9.6 Mm^3 (+83%)	12.9 Mm^3 (-20%)	38.8 Mm^3 (-30%)	21.4 Mm^3 (-11%)	251.6 Mm^3 (-14%)
TOTAL forestland footprint per category	44.8 Mha (-24%)	11.8 Mha (-14%)	4.5 Mha (+69%)	5.3 Mha (-26%)	15.2 Mha (-36%)	8.3 Mha (-22%)	89.9 Mha (-23%)

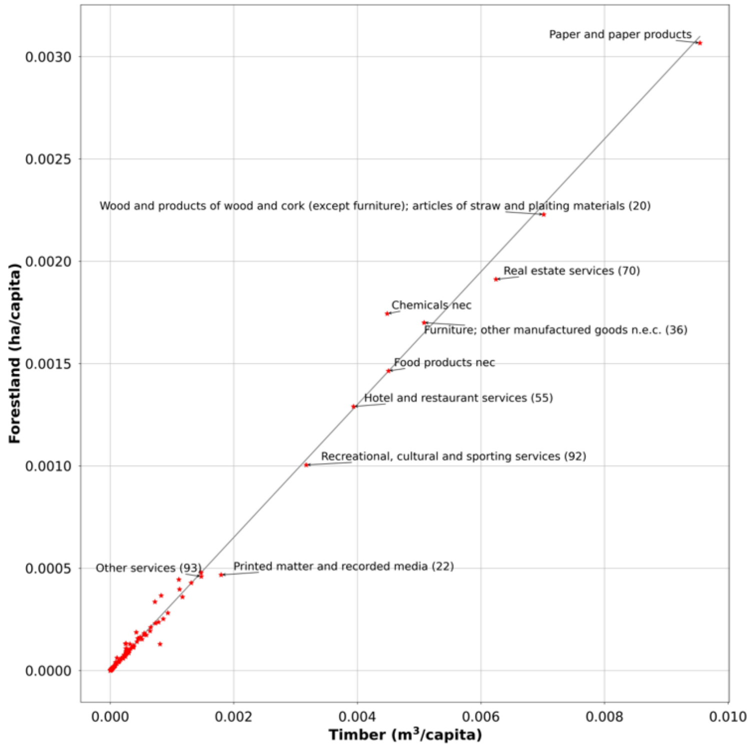

Figure B-1. Per capita timber vs forestland footprints of African household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

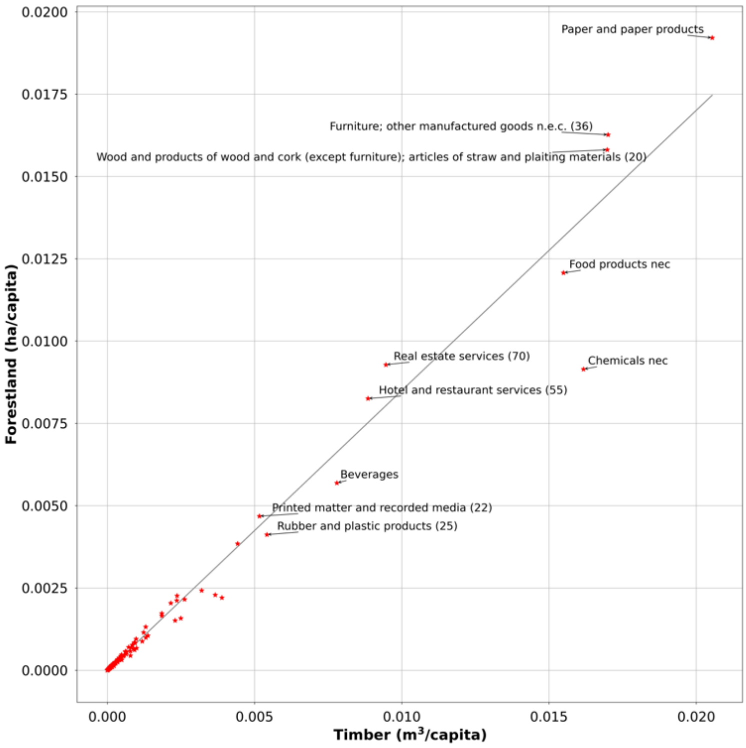

Figure B-2. Per capita timber vs forestland footprints of American household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

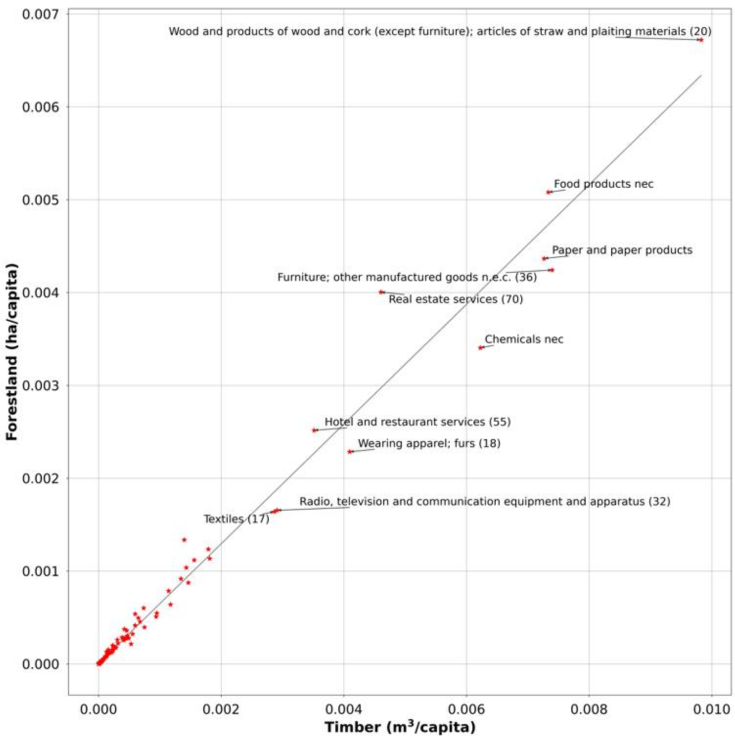

Figure B-3. Per capita timber vs forestland footprints of Asia-Pacific household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

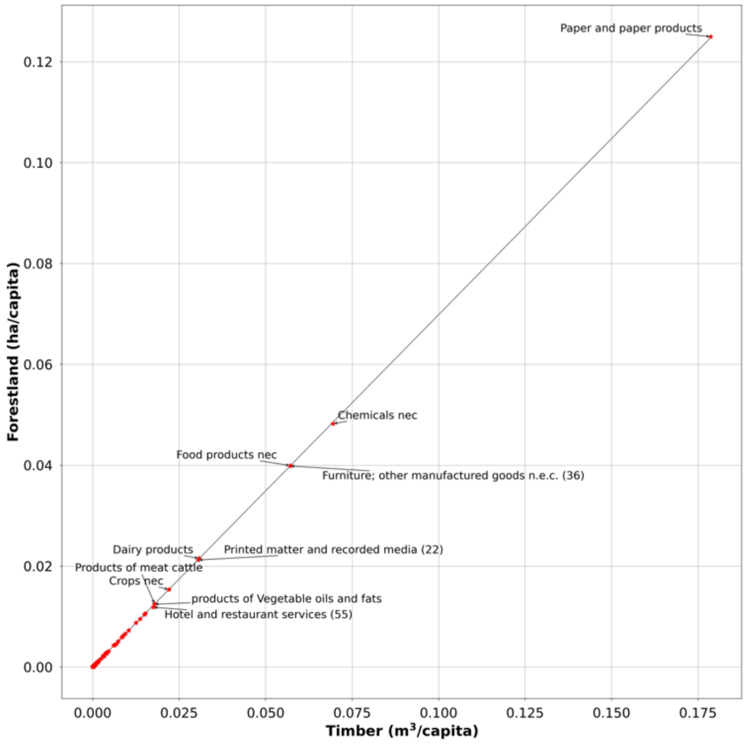

Figure B-4. Per capita timber vs forestland footprints of Brazilian household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

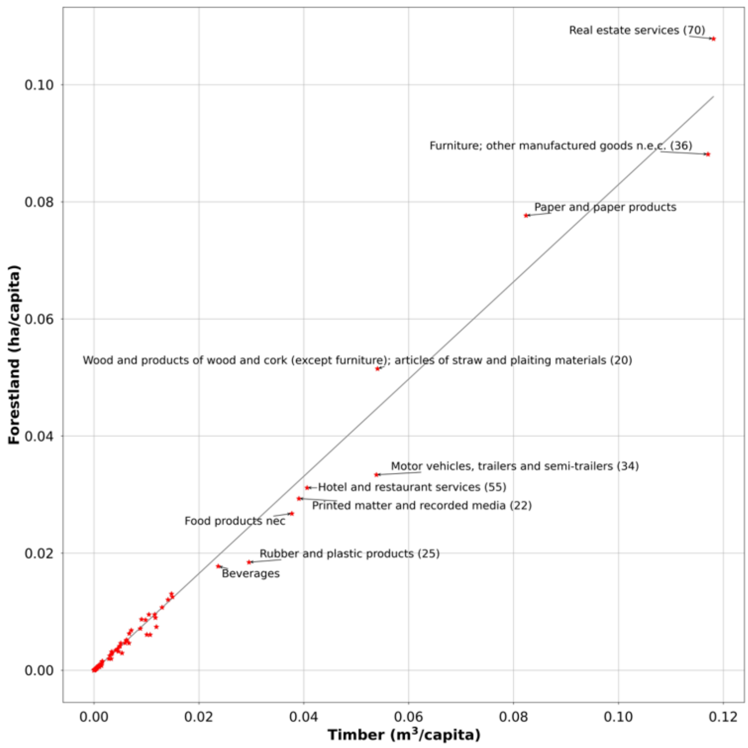

Figure B-5. Per capita timber vs forestland footprints of Canadian household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

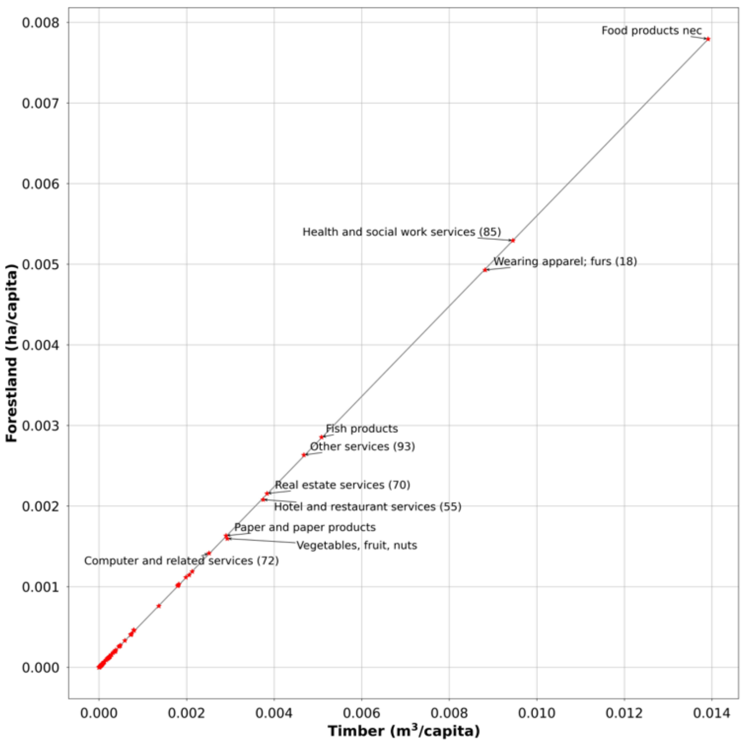

Figure B-6. Per capita timber vs forestland footprints of Chinese household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

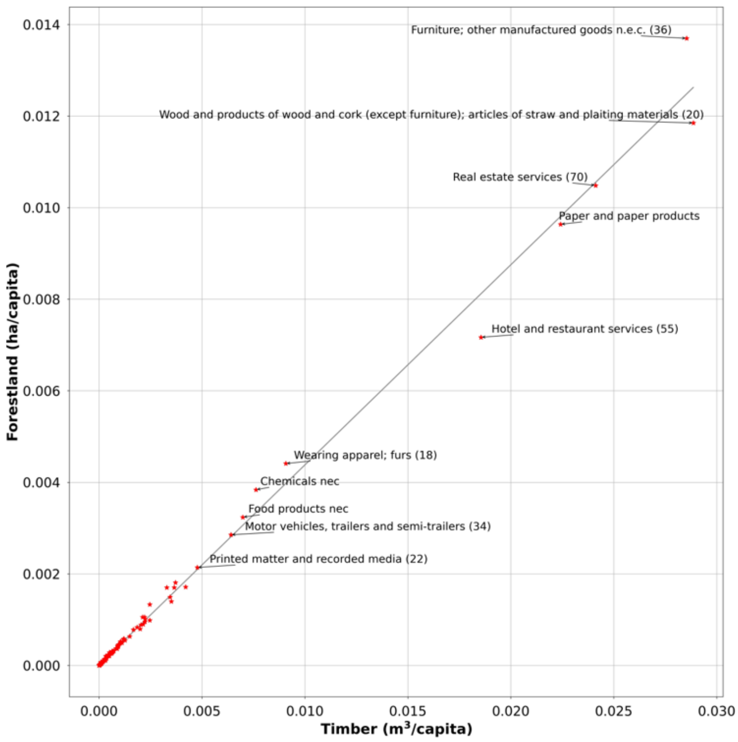

Figure B-7. Per capita timber vs forestland footprints of European household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

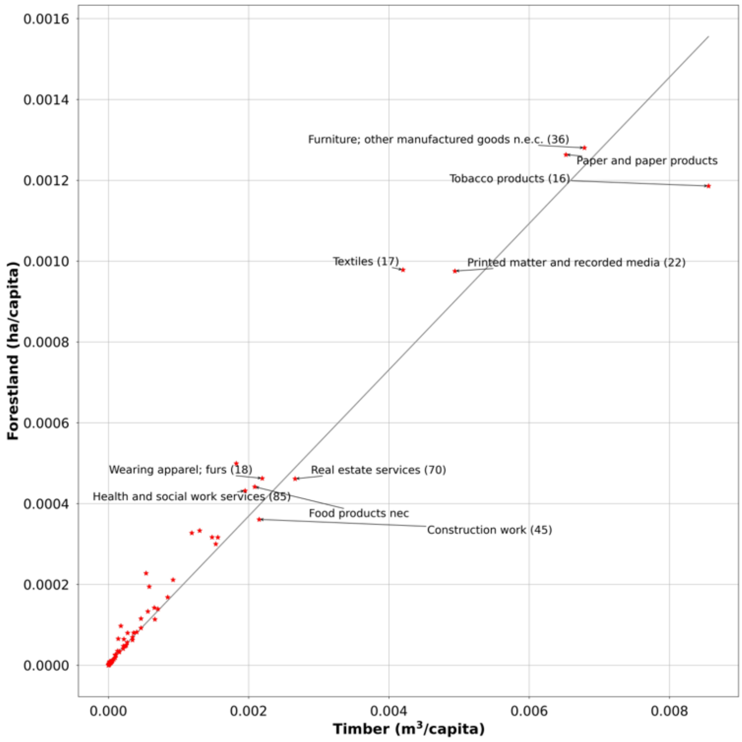

Figure B-8. Per capita timber vs forestland footprints of Indian household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

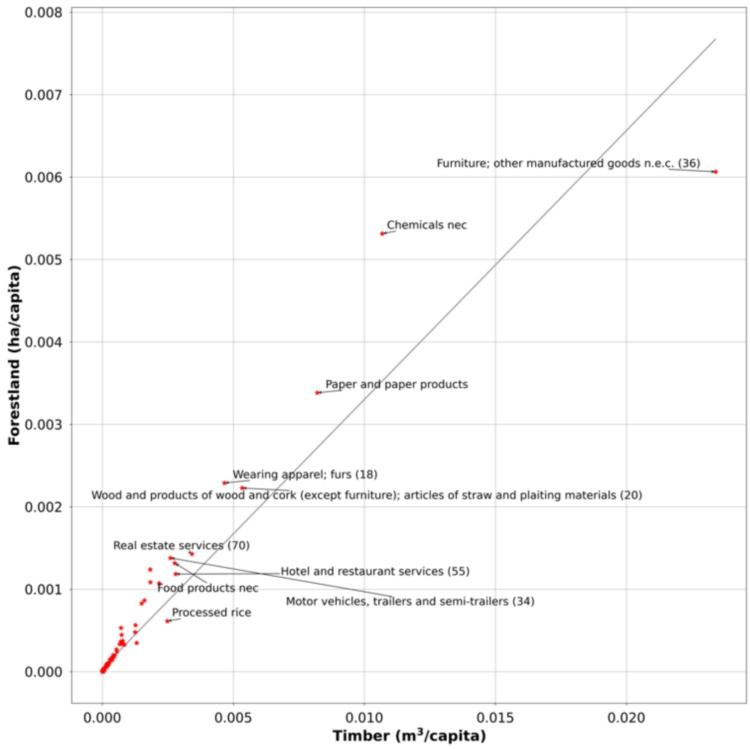

Figure B-9. Per capita timber vs forestland footprints of Middle Eastern household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

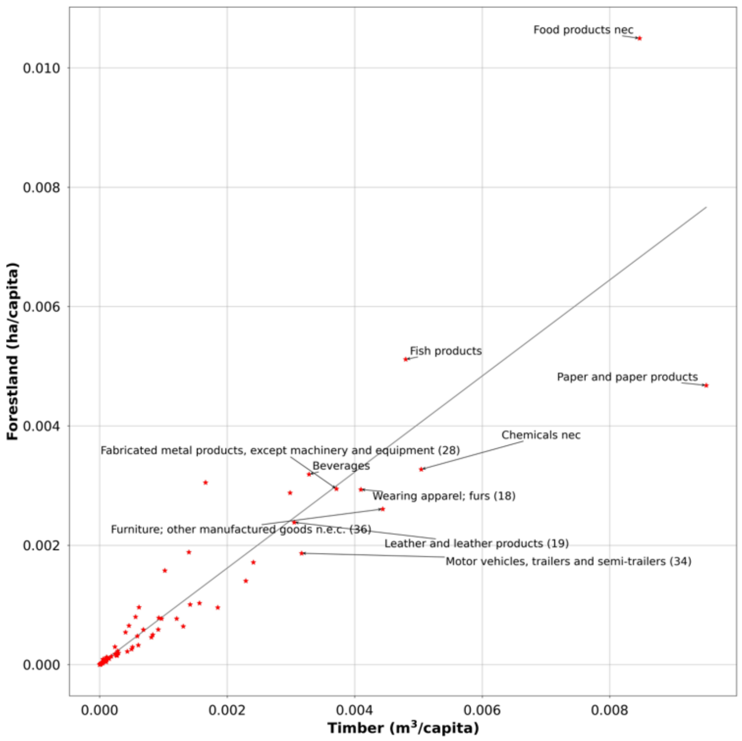

Figure B-10. Per capita timber vs forestland footprints of Russian household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

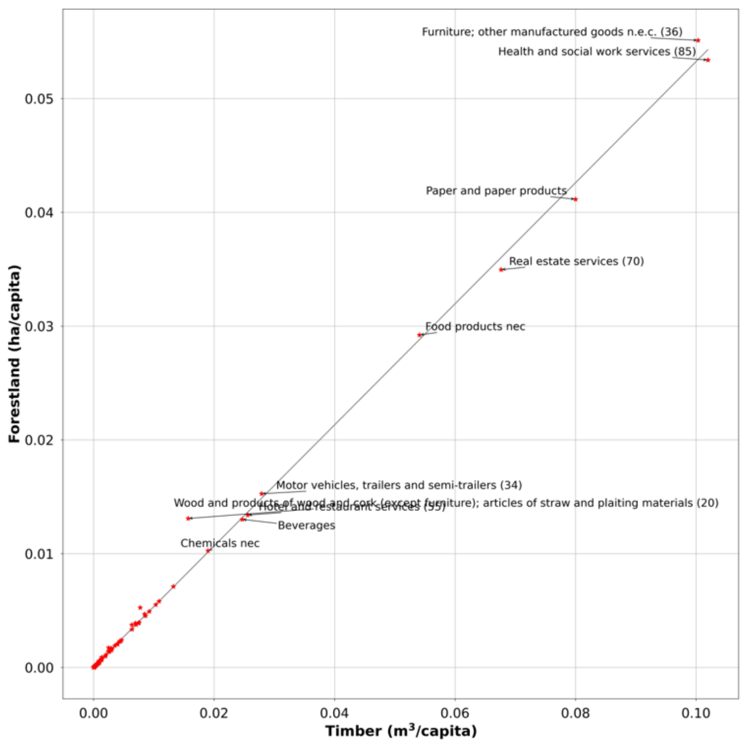

Figure B-11. Per capita timber vs forestland footprints of USA household product consumption in 2011, with indication of the top 10 product categories without the largest 'products of forestry'.

Appendix C. Sustainable productivity calculation

The maximum annual productivity is calculated by multiply the NAI ($m^3.ha^{-1}.year^{-1}$) with the FAWS (ha productive forest).

The FAWS is provided in Table C-1 and is fully based on low (minimum literature or 75% of realistic), realistic (best estimate semi-natural + plantation forests) and high (all forest area except protected) estimates by O'Brien (2016). RoW regions were calculated by subtracting separate EXIOBASE countries from the total continent values (see 'Region' in Table C-1). As there is no Middle East value in O'Brien (2016), the values of countries were summed up. It can be seen that WA and WL are further split up in respectively WA (Oceania) and WA (Asia), and WL (C-America) and WL (S-America). The reasoning behind this is to attempt improving the timber productivity estimate as the NAI data in these regions strongly differed. Malta and Taiwan could not be determined due to lacking data.

The NAI is more complex, with the values used for the sustainability comparison presented in Table C-1. As a source, NAI values from the Global Forest Resources Assessment (FAO, 2015) and State of Europe's Forests (Forest Europe, 2015) were preferred where available. The chosen year for this value was 2010 or the closest year to 2010. In case a value was found in both reports, the average was taken. For the remaining regions except RoW, O'Brien (2016) NAI data on semi-natural forests were taken. In the case of RoW regions, realistic continent averages as calculated by O'Brien (2016) were used, except for RoW Middle East. As clear average exists for RoW Middle East, and the NAI in this region is likely lower, the low Asian continent average was used, which at 1,38 $m^3.ha^{-1}.year^{-1}$ is close to the 1.35 $m^3.ha^{-1}.year^{-1}$ calculated in the supplements of Egenolf et al. (2021).

Multiplication of both provides the total annual productivity for each region. After multiplication, WA (Oceania) was again summed with WA (Asia) to WA, and WL (C-America) with WL (S-America) to WL, to be consistent with the footprint calculations.

Comparison to the household timber footprint calculations is however not yet possible. The timber stressors used to determine the footprints originally came from FAOSTAT (Stadler et al., 2018c). Such data is however reported without bark and harvest residues (Egenolf et al., 2021; O'Brien & Bringezu, 2018), while the NAI is presented including these losses. Based on literature, Egenolf et al. (2021) adjusted timber volumes for 12% loss of bark ($timber\ volume * \left(\frac{1}{0.88}\right)$) and a further 10% harvest loss ($timber\ volume * \left(\frac{1}{0.88}\right) * \left(\frac{1}{0.9}\right)$). Ultimately, both the values of domestically produced timber and consumed timber were adjusted by this multiplication.

Table C-1. Forest Available for Wood Supply for all EXIOBASE regions based on O'Brien (2016), and Net Annual Increment for all EXIOBASE regions using different sources. Blue indicates the average from GFRA 2015 and SOEF 2015 is taken, yellow indicates O'Brien (2016), red indicates GFRA (FAO, 2015) as only source and green indicates SOEF (Forest Europe, 2015) as only source.

Region	Low FAWS O'Brien (2016)	Realistic FAWS O'Brien (2016)	High FAWS O'Brien (2016)	NAI GFRA 2015 (m^3/ha)	NAI SOEF 2015 (m^3/ha)	O'Brien (2016) NAI (m^3/ha)	NAI used (m^3/ha)
Austria	2332	3343	3228	7,1	7,5		7,3
Belgium	373	672	469	7,5	6,9		7,2
Bulgaria	2864	2867	3614	3,8	6		4,9
Croatia	1741	1747	1866	4,3	4,7		4,5
Cyprus	41	42	78	1	1,1		1,05
Czech Republic	1993	2330	1917	9,1	8,9		9
Denmark	446	581	504	8,6	11,3		9,95
Estonia	1751	2013	2004	5,6	5,7		5,65

Finland	19277	19869	20232	4,4	4,8		4,6
France	14470	15147	15641	5,2	5,3		5,25
Germany	8196	10568	8322	11,2	10,9		11,05
Greece	3595	3591	3739		1,3		1,3
Hungary	1299	1726	1605	7,1	5,7		6,4
Ireland	312	318	681	11,5	11		11,25
Italy	4117	8086	5884	3,2	4,1		3,65
Latvia	2650	3138	2744	6,6	6,2		6,4
Lithuania	1706	1875	1727	5,8	6		5,9
Luxembourg	29	86	76		7,5		7,5
Malta	N/A	N/A	N/A				
Netherlands	274	295	282	7,4	9,2		8,3
Poland	3828	8532	9150	8	7,7		7,85
Portugal	1822	2039	2756		8,6		8,6
Romania	3155	5193	4827	8,6	5,7		7,15
Slovakia	1276	1775	829	7	7,6		7,3
Slovenia	526	1175	1012	8,7	7,1		7,9
Spain	11994	14915	15674	1,9	2,4		2,15
Sweden	20538	20554	26768	3,3	4		3,65
Norway	6039	6419	9898	2,3	3,1		2,7
Switzerland	496	1200	1150	7,7	7,5		7,6
United Kingdom	2108	2411	2736	7,6	7,6		7,6
Brazil	21990	57147	429981			2,9	2,9
Canada	116201	125863	285275			1,81	1,81
China	65160	84813	182190	3,5			3,5
India	21935	22400	48660			1	1
Russia	527542	677204	791518	1,3			1,3
USA	198123	208095	273797	3			3
Turkey	6595	8635	11065	3,2	4,6		3,9
Mexico	8571	18000	56314			1,25	1,25
Japan	4246	6468	11830	2,9			2,9
Taiwan	N/A	N/A	N/A				
South-Korea	3593	4791	5413	4,9			4,9
Indonesia	28700	50049	56621	2,5			2,5
South-Africa	1756	3000	8294			8	8
Australia	15905	16438	122679			2,11	2,11
WA (Oceania part): Total Oceania without Australia	7307	12303	37845			3,73	3,73
WA (Asia part): Total Asia without Japan, Indonesia, India, Japan, China, Taiwan, Turkey, Cyprus, S-Korea, WM	37408	80395	130163			2,18 Realistic Asia average	2,18
WF: Total Africa without	122709	235237	575728			1,72	1,72

S-Africa and Egypt (= in WM)						Realistic Africa average	
WE: Total Europe without EU countries, UK, Norway, Switzerland and Russia, plus Cyprus (to balance, included in Asian content)	12884	17031	21539		3,9		3,9
WL (Central-America part): Total C-America	5335	9958	17712			1,8 Realistic C-America average	1,8
WL (S-America part): Total S-America without Brazil	44908	96666	296073			4,59 Realistic S-America average	4,59
WM: Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Saudi Arabia, Syria, United Arab Emirates, Yemen	3217	4463	12767			1,38 Low Asia average (no Middle East value available)	1,38

Table C-2. Comparison of forestland footprint of household consumption and domestic forestland in use for global household consumption to three FAWS levels in O'Brien (2016).

Region	Forestland footprint (Mha)	% Low FAWS O'Brien (2016)	% Realistic FAWS O'Brien (2016)	% High FAWS O'Brien (2016)	Forest area in use (Mha)	% Low FAWS O'Brien (2016)	% Realistic FAWS O'Brien (2016)	% High FAWS O'Brien (2016)
Austria	2,7	117%	82%	85%	2,3	98%	68%	71%
Belgium	2,1	555%	308%	441%	0,4	102%	57%	81%
Bulgaria	1,7	58%	58%	46%	2,5	86%	86%	68%
Croatia	0,6	35%	35%	33%	1,2	71%	70%	66%
Cyprus	0,1	161%	157%	85%	0,0	2%	2%	1%
Czech Republic	1,3	66%	57%	69%	1,4	71%	61%	74%
Denmark	0,9	201%	154%	178%	0,3	74%	57%	65%
Estonia	0,3	16%	14%	14%	1,0	59%	51%	52%
Finland	5,2	27%	26%	26%	5,1	27%	26%	25%
France	11,6	80%	77%	74%	6,2	43%	41%	40%
Germany	19,5	238%	185%	235%	8,0	98%	76%	97%
Greece	2,5	68%	69%	66%	1,7	46%	46%	45%
Hungary	1,7	131%	99%	106%	1,4	105%	79%	85%
Ireland	0,8	269%	264%	123%	0,4	120%	118%	55%
Italy	9,6	233%	119%	163%	3,8	93%	47%	65%
Latvia	0,2	8%	7%	8%	1,5	58%	49%	56%
Lithuania	1,1	65%	59%	64%	1,4	84%	76%	83%
Luxembourg	0,2	553%	187%	211%	0,0	147%	50%	56%
Malta	0,0	N/A	N/A	N/A	0,0	N/A	N/A	N/A

Netherlands	1,4	512%	475%	497%	0,2	84%	78%	81%
Poland	5,3	138%	62%	58%	5,9	153%	69%	64%
Portugal	1,3	69%	62%	46%	0,6	33%	29%	22%
Romania	5,5	175%	106%	114%	5,6	177%	107%	116%
Slovakia	0,8	62%	45%	95%	1,3	100%	72%	155%
Slovenia	1,0	196%	88%	102%	0,9	175%	78%	91%
Spain	6,4	53%	43%	41%	3,6	30%	24%	23%
Sweden	6,2	30%	30%	23%	8,1	39%	39%	30%
Norway	3,8	63%	59%	38%	3,7	62%	58%	38%
Switzerland	2,1	423%	175%	182%	0,7	137%	57%	59%
United Kingdom	11,1	526%	460%	405%	1,2	58%	50%	44%
Brazil	120,9	550%	212%	28%	132,8	604%	232%	31%
Canada	43,9	38%	35%	15%	68,7	59%	55%	24%
China	133,8	205%	158%	73%	87,5	134%	103%	48%
India	27,9	127%	125%	57%	8,8	40%	39%	18%
Russia	307,6	58%	45%	39%	363,3	69%	54%	46%
USA	117,8	59%	57%	43%	89,4	45%	43%	33%
Turkey	8,1	123%	94%	74%	4,6	70%	53%	42%
Mexico	15,1	177%	84%	27%	14,1	164%	78%	25%
Japan	21,9	517%	339%	185%	7,6	179%	118%	64%
Taiwan	2,7	N/A	N/A	N/A	1,0	N/A	N/A	N/A
South-Korea	10,7	297%	223%	197%	2,7	74%	55%	49%
Indonesia	19,9	69%	40%	35%	21,9	76%	44%	39%
South-Africa	2,7	152%	89%	32%	2,4	138%	81%	29%
Australia	12,4	78%	76%	10%	19,2	121%	117%	16%
WA	62,4	139%	67%	37%	101,2	226%	109%	60%
WF	141,8	116%	60%	25%	164,5	134%	70%	29%
WE	13,7	106%	80%	64%	17,4	135%	102%	81%
WL	141,5	282%	133%	45%	147,7	294%	139%	47%
WM	14,8	459%	331%	116%	0,9	29%	21%	7%

Table C-3. Comparison of timber footprint of household consumption and domestic timber production for global household consumption to three calculated levels of NAI productivity. Footprints are 22% adjusted for 12% loss of bark and 10% additional harvest loss in FAOSTAT data.

Region	**Timber footprint (Mm^3), 22% adj**	**100% NAI**	**90% NAI**	**80% NAI**	**Timber produced (Mm^3), 22% adj**	**100% NAI**	**90% NAI**	**80% NAI**
Austria	14,4	59%	66%	74%	14,6	60%	67%	75%
Belgium	6,4	132%	147%	165%	3,5	73%	81%	91%
Bulgaria	4,1	29%	32%	36%	5,9	42%	46%	52%
Croatia	1,9	24%	27%	30%	4,0	51%	57%	64%
Cyprus	0,2	423%	470%	529%	0,0	4%	5%	5%
Czech Republic	7,2	34%	38%	43%	10,5	50%	56%	63%
Denmark	2,9	50%	56%	63%	2,2	38%	42%	47%
Estonia	1,1	10%	11%	12%	4,7	41%	46%	51%
Finland	12,4	14%	15%	17%	21,1	23%	26%	29%

France	45,8	58%	64%	72%	31,3	39%	44%	49%
Germany	80,9	69%	77%	87%	50,2	43%	48%	54%
Greece	4,3	92%	102%	115%	1,5	31%	35%	39%
Hungary	7,4	67%	74%	84%	6,6	60%	67%	75%
Ireland	3,0	83%	92%	104%	2,1	58%	65%	73%
Italy	24,6	83%	92%	104%	6,1	21%	23%	26%
Latvia	0,7	4%	4%	5%	8,8	44%	49%	55%
Lithuania	4,6	42%	47%	52%	6,7	60%	67%	75%
Luxembourg	0,4	68%	75%	85%	0,2	29%	32%	36%
Malta	0,1	N/A	N/A	N/A	0,0	N/A	N/A	N/A
Netherlands	4,0	164%	182%	205%	0,7	29%	32%	36%
Poland	22,0	33%	37%	41%	29,5	44%	49%	55%
Portugal	5,1	29%	32%	36%	6,7	38%	42%	48%
Romania	14,3	38%	43%	48%	14,1	38%	42%	48%
Slovakia	3,6	28%	31%	35%	6,9	53%	59%	66%
Slovenia	3,5	38%	42%	48%	3,3	36%	40%	45%
Spain	19,6	61%	68%	76%	11,5	36%	40%	45%
Sweden	23,2	31%	34%	39%	34,2	46%	51%	57%
Norway	9,6	55%	62%	69%	7,4	43%	48%	53%
Switzerland	6,2	68%	76%	86%	3,1	34%	37%	42%
United Kingdom	33,2	181%	201%	227%	6,8	37%	41%	46%
Brazil	219,1	132%	147%	165%	239,5	144%	161%	181%
Canada	62,8	28%	31%	34%	87,2	38%	43%	48%
China	302,0	102%	113%	127%	255,6	86%	96%	108%
India	127,1	568%	631%	709%	106,6	476%	529%	595%
Russia	199,1	23%	25%	28%	224,8	26%	28%	32%
USA	274,6	44%	49%	55%	237,3	38%	42%	48%
Turkey	31,4	93%	104%	117%	22,6	67%	75%	84%
Mexico	31,2	139%	154%	173%	28,2	125%	139%	157%
Japan	37,6	200%	223%	250%	8,1	43%	48%	54%
Taiwan	5,1	N/A	N/A	N/A	1,0	N/A	N/A	N/A
South-Korea	20,1	86%	95%	107%	4,4	19%	21%	23%
Indonesia	36,3	29%	32%	36%	38,8	31%	34%	39%
South-Africa	25,5	106%	118%	133%	28,6	119%	132%	149%
Australia	14,2	41%	46%	51%	13,7	40%	44%	49%
WA	144,0	65%	72%	81%	233,8	106%	117%	132%
WF	559,7	138%	154%	173%	658,2	163%	181%	203%
WE	33,9	51%	57%	64%	43,0	65%	72%	81%
WL	179,0	39%	43%	48%	172,1	37%	41%	47%
WM	55,4	900%	1000%	1125%	17,7	288%	320%	360%