# Globalization of forest land use: increasing threats to climate-vulnerable regions

**Abstract:** Given the increasing influence of international trade on regional land use, this paper presents a comprehensive overview of forest land use across global supply chains by means of embodiment accounting based on EXIOBASE 3 database, with a specific focus on the climate vulnerability and adaptation readiness of supply chain agents. Globally, 2268.3 million hectares (Mha) of forest land was exploited for forestry in 2015, while 30% was associated with export production, mainly sourced from Russia, Canada, Africa, South America and tropical and subtropical Asia-Pacific and linked to the final consumption of developed (e.g. the EU, the USA and Japan) and emerging (e.g. China and India) economies. During 2000-2015, forest land exploited in climate-vulnerable regions rose to 689.4 Mha, contributing over 50% of the overall increase in global forest land exploitation. Forest land use displaced from China and India to these regions increased by 2.6 and 3.3 times, respectively, due to escalating imports from tropics and subtropics (especially Asia-Pacific), where the readiness to take adaptation actions was also low. For the EU and the USA, virtual forest land use sourced from these sources remained large in absolute magnitude despite decreasing import volume. Therefore, transnational mutual efforts are needed to secure local forestry of climate-vulnerable regions, improve the resilience of global supply chains and mitigate negative influence on other sustainable development goals supported by forest ecosystems.

**Keywords:** Virtual forest land, land use displacement, climate vulnerability, climate change, global supply chains, sustainable development goals

## Introduction

Forest land, occupying more than 31% of global total land area (WB, 2019), is not only essential for biodiversity conservation (Gibson et al., 2011; Van de Perre et al., 2018) and climate regulation (Canadell and Raupach, 2008; Murdiyarso et al., 2015), but also plays a significant role in improving food security (Hickey et al., 2016; Mbow et al., 2014) and reducing rural poverty (Mohammad Abdullah et al., 2016; Oldekop et al., 2019). However, global forest area is declining rapidly, especially in the tropics and subtropics (Hansen et al., 2013). Deforestation from agricultural encroachment has been widely concerned (Austin et al., 2019; Curtis et al., 2018; Ordway et al., 2019), yet forest degradation from forestry has so far received relatively less attention. As a matter of fact, forest degradation can match or even surpass deforestation (e.g. in the Amazon Basin) (Foley et al., 2007; Hosonuma et al., 2012). Therefore, a holistic profile of forest land use is pivotal for the conservation and restoration of degraded forest ecosystems.

Local exploitation of forest land is usually driven by external demand in the context of globalization (Meyfroidt et al., 2013). Since the production and consumption are increasingly spatially separated and connected through global supply chains (WTO, 2019), an economy can indirectly utilize distant forest land by importing finished forest-based products. Due to forest scarcity and environmental concerns, an increasing number of countries tend to displace forest land use outside their borders, putting great burden on Africa, Southeast Asia and South America (Pendrill et al., 2019), which may be the underlying reason for the forest cover increase among many high- and middle-income countries along with the rife decrease within low-income countries (FAO, 2016). As a consequence, regional efforts to preserve forests can be offset by overexploitation elsewhere, highlighting the necessity to uncover the driving effects of global consumption and trade on regional forest land exploitation.

The area of forest land use displacement is not the only factor that matters, it is also significant to unveil the climate vulnerability of producing regions. Deforestation and forest degradation following forest land use have incurred substantial influence on regional and global climate (e.g. due to changes in carbon and hydrological cycles) (Malhi et al., 2008; Shukla et al., 1990) while climate change in turn has threatened forest ecosystems through varying temperature, precipitation, frequency and severity of natural hazards (Kirilenko and Sedjo, 2007; Lindner et al., 2010). These variabilities not only aggravate the instability of local production but also undermine the resilience of global supply chains of forest-based products. Moreover, the influence can extend beyond forestry to other life-supporting aspects, including food, water, health, ecosystem services and so on (Sonwa et al., 2012). The vulnerability to climate change and the readiness to take adaptation actions varied greatly from country to country, due to diverse ecological, economic, governance and social environments (Chen et al., 2015; Réjou-Méchain et al., 2021). Therefore, the eco-environmental and socio-economic consequences of the displacement of the same area of forest land use can be distinctively different. Considering the pressing and persistent issues of climate change, trade analysis integrating climate vulnerability and adaptation readiness is especially crucial to help supply chain agents recognize the far-reaching impacts of their production/consumption and take precautions against potential perturbations through global mutual efforts, which facilitate both the resilience of global supply chains and the achievement of multi-dimensional sustainable development goals.

The notion of virtual land (aka. land footprint), defined as the total land area required to produce a kind of good or service, has been widely adopted to measure different types of land use (Guo et al., 2019; Kan et al., 2021; Kastner et al., 2014), whereas relatively less efforts have been devoted to analyzing virtual forest land. Several studies analyzed global virtual timber trade (Kastner et al., 2011; Meyfroidt et al., 2010; Zhang et al., 2020) and Weinzettel et al. estimated virtual forest land trade based on the yields of forest products (Weinzettel et al., 2013), but there may be large uncertainties when converting yields to land use. Yu and colleagues used data on forest land use directly to assess the tele-connection between regional consumption and global land use (Yu et al., 2013), while both Weinzettel et al. and Yu et al. concentrated on the panorama of total land use in a single year. Specific analyses on forest land use and its temporal trends are still lacking. Moreover, none of previous virtual timber/forest land studies have considered regions' climate vulnerability and adaptation readiness.

Given all of the above, this paper endeavors to trace forest land use across global supply chains for the world economy, with a specific focus on climate vulnerability and adaptation readiness of supply chain agents. Temporal trends of forest land use during

2000-2015 are investigated and a comprehensive picture for 2015 is presented. By providing a systematic overview of virtual forest land use, this paper aims to provide data support and policy implications for policy makers to make informed decisions regarding both sustainable forest management and improvement of supply chain resilience without interfering the achievement of other sustainable development goals.

# 2. Methods and data sources

## 2.1 Embodiment accounting

Virtual forest land is calculated by means of embodiment accounting, based on input-output analysis (IOA), which has been applied to study materials (Bruckner et al., 2012; Giljum et al., 2015; Wiedmann et al., 2015), total primary energy (Chen and Wu, 2017; Kan et al., 2019a; Moreau and Vuille, 2018), oil (Wu and Chen, 2019), natural gas (Kan et al., 2020; Kan et al., 2019b), coal (Wu and Chen, 2018), water (Ewing et al., 2012; Feng et al., 2014; Guan and Hubacek, 2007), carbon emissions (Feng et al., 2015; Feng et al., 2013; Guan et al., 2018) and so on. Leontief is regarded as the pioneer to integrate environmental accounts into IOA (Leontief, 1970). Bullard and Herendeen adapted IOA to calculate energy embodied in goods and services for the United States, on the basis of an energy balance model (Bullard and Herendeen, 1975a, b; Bullard et al., 1978). By integrating the embodiment theory in systems ecology (Odum, 1983), the model was further extended by Chen and colleagues to study various ecological elements (Kan et al., 2020; Liu et al., 2020; Wu et al., 2018; Wu et al., 2019).

From the biophysical perspective, practically everything in the earth can be considered as a direct or indirect product of the energy and materials that underpin its formation. Industrial capital, intermediate and final products created by the economic process are all maintained by exogenous environmental input (Costanza, 1980). The embodiment theory was therefore developed to probe into the biophysical support of the economic system (Odum, 1983, 1995; Wu et al., 2018). Just as every commodity is regarded to have economic value measured by currency in the monetary accounting framework, the theory reveals that every product embodies the resource use required to produce it, i.e. virtual resource use, no matter whether the product is for intermediate or final use. Another basis of the embodiment accounting is the objective law of conservation of resource use, such as conservation of embodied energy (Bullard and Herendeen, 1975a, b; Hannon et al., 1983; Herendeen, 2004). In other words, the total input of virtual resource use to a system is equal to the system's total output. The biophysical balance can be applied to every system, including each economic sector.

In this paper, the embodiment accounting is carried out with the help of the multi-regional input-output model, which simulates the world as a $m$ region $\times$ $n$ sector economic system and captures transactions between sectors in intermediate trade and sectoral sales to final consumers in final market. Once forest land is exploited, it enters the economic system and exists as product embodiments. Though the physical forest land is immovable, the utility of forest land can be transferred along with currency flows and goods/services flows (Hilten, 2019), from primary exploiters to final consumers.

Sectoral input of virtual forest land consists of forest land exploited directly by the sector and that embodied in imported intermediate products, while the total output is comprised of forest land use embodied in all the sector's production. Then the biophysical balance equation for sector *i* in region *r* can be written as:

$$fl_i^r + \sum_{s=1}^{m}\sum_{j=1}^{n}(\varepsilon_j^s\, z_{ji}^{sr}) = \varepsilon_i^r(\sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} f_i^{rs}) \qquad (1)$$

where $fl_i^r$ denotes forest land exploited directly by sector *i*. $z_{ji}^{sr}$ represents the monetary value of intermediate products supplied by sector *j* in region *s* to sector *i*. $f_i^{rs}$ stands for monetary value of final products traded from sector *i* to region *s*. $\varepsilon_i^r$ is the virtual forest land intensity, representing forest land use embodied in the sector's unit output. Considering the biophysical equations for all the sectors, equation (1) can be transformed as:

$$\boldsymbol{FL} + \boldsymbol{\varepsilon Z} = \boldsymbol{\varepsilon X} \qquad (2)$$

where $\boldsymbol{FL} = (fl_i^r)_{1\times mn}$, $\boldsymbol{Z} = (z_{ij}^{rs})_{mn\times mn}$, $\boldsymbol{\varepsilon} = (\varepsilon_i^r)_{1\times mn}$ and $\boldsymbol{X} = \mathrm{diag}(x_i^r)_{mn\times mn}$ ($x_i^r = \sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} f_i^{rs}$). Therefore, $\boldsymbol{\varepsilon}$ can be calculated as:

$$\boldsymbol{\varepsilon} = \boldsymbol{FL}(\boldsymbol{X} - \boldsymbol{Z})^{-1} \qquad (3)$$

The amount of forest land use embodied in the products provided by sector *i* in region *r* can be calculated as the monetary value of the products multiplied by corresponding intensity $\varepsilon_i^r$. Then virtual forest land use associated with final consumption and international trade can be obtained by summing up forest land use embodied in all the consumed or traded products. Therefore, for region *r*, virtual forest land use in its final consumption ($VF^r$), its intermediate imports ($VFI^r_{int}$) and exports ($VFE^r_{int}$), final imports ($VFI^r_{fin}$) and exports ($VFE^r_{fin}$) can be expressed as:

$$VF^r = \sum_{s=1}^{m}\sum_{j=1}^{n} \varepsilon_j^s f_j^{sr} \tag{4}$$

$$VFI^r_{int} = \sum_{s=1(s\neq r)}^{m}\sum_{j=1}^{n}\sum_{i=1}^{n} (\varepsilon_j^s \, z_{ji}^{sr}) \tag{5}$$

$$VFE^r_{int} = \sum_{s=1(s\neq r)}^{m}\sum_{j=1}^{n}\sum_{i=1}^{n} (\varepsilon_i^r \, z_{ij}^{rs}) \tag{6}$$

$$VFI^r_{fin} = \sum_{s=1(s\neq r)}^{m}\sum_{j=1}^{n} (\varepsilon_j^s f_j^{sr}) \tag{7}$$

$$VFE^r_{fin} = \sum_{s=1(s\neq r)}^{m}\sum_{i=1}^{n} (\varepsilon_i^r f_i^{rs}) \tag{8}$$

## 2.2 Data sources

The input-output tables are taken from EXIOBASE 3, due to its high product resolution (i.e. 200 products with products of forestry, logging and related services separated from agricultural products) matched with land use data for multiple land covers (including cropland, grazing land and forest land) (Stadler et al., 2018). It should be noted that, the end year of land extensions in original EXIOBASE 3 data series is 2011, so statistics of land use are collected from EXIOBASE 3rx, which provides land updates to 2015 for 214 countries and regions. EXIOBASE 3 assumes marginally used areas (grid cells on the map that contain both used and unused land) as uses with low intensities (e.g. hunting) and does not attribute this part to forestry operations. This paper only considers forest land use by forestry sectors. With reference to *Global Forest Products – Facts and Figures* (FAO, 2018a), *Yearbook of Forest Products* (FAO, 2019b) and *Forestry Production and Trade* statistics (FAO, 2019a), forest products in this paper refer to roundwood and various derived products, such as sawn wood, veneer sheets, wood-based panels, wood pulp, paper, paperboard, wood fuel, wood chips, wood particles and wood pellets. Non-forest products refer to other products that are indirectly associated with forest land exploitation.

The world is aggregated into 44 major economies and 5 *rest of world* (RoW) composite regions in EXIOBASE 3 (please see the Supplementary Information for the classification). Some of the regions are further aggregated in this paper for research purpose. The EU includes 28 member countries, China includes EXIOBASE 3 categories of *China* and *Taiwan, China*. To distinguish from EXIOBASE 3 *RoW Middle East* and *RoW Africa* categories, Middle East covers *Turkey* and *RoW Middle East* and Africa covers *South Africa* and *RoW Africa*. Population data are derived from the World Bank (WB, 2017).

Data on climate vulnerability and adaptation readiness are taken from University of Notre Dame Global Adaptation Index (ND-GAIN) Country Index (Chen et al., 2015). Vulnerability reflects the propensity to be adversely affected by climate disruption, which is measured by sensitivity, exposure and adaptive capacity. Readiness assesses the ability to leverage public and private investments to take adaptation actions in the face of climate hazards, which is measured by economic, governance and social readiness. Due to its inclusiveness, feasibility and comparability, ND-GAIN Country Index and similar conceptual framework have been applied in several studies (Lindner et al., 2010; Scarano and Ceotto, 2015; Scheelbeek et al., 2020; Sonwa et al., 2012). Countries are assigned to 8 categories based on their vulnerability scores or readiness scores. With reference to Scheelbeek et al. (Scheelbeek et al., 2020), countries with the highest to the fourth highest levels are considered to have relatively high climate vulnerability / low adaptation readiness. This paper uses average scores over 2000-2015 for classification.

# 3. Results

## 3.1 Virtual forest land use associated with final consumption

At a global scale, forest land use amounted to 2268.3 million hectares (Mha) in 2015. As shown in Fig. 1, China was the leading final consumer of virtual forest land use (325.7 Mha), followed by Africa (292.7 Mha), Russia (266.4 Mha), the USA (266.1 Mha), RoW America (218.8 Mha) and Brazil (138.1 Mha). Virtual forest land use of other countries and regions each were less than 100 Mha. For China, the EU, the USA, India and Japan, forest land use associated with final consumption was greater than local forest land exploitation, which means a large amount of forest land use was displaced to other regions. The situation was reversed for Russia, Brazil, Canada, Australia, Mexico and many other African, South American and Asia-Pacific countries, which manifests their role as suppliers who exploited local forests for downstream use both at home and abroad.

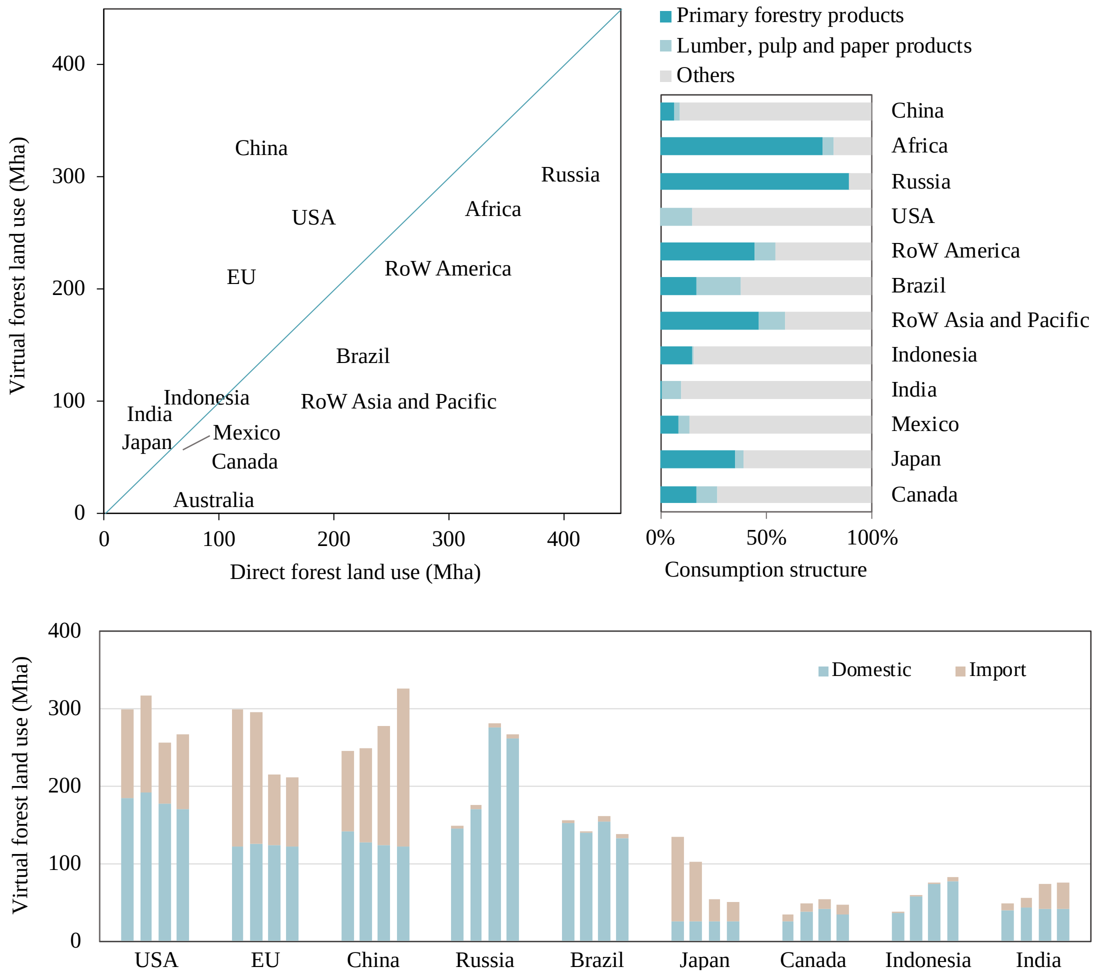



**Fig. 1 Virtual forest land use in final consumption**

The upper left chart compares direct and virtual forest land use in 2015 for EXIOBASE 3 countries and regions as well as EU members as a whole, with the size of the circles denoting per capita virtual forest land use. The upper right chart presents sectoral contribution to virtual forest land use for dominant final consumers. The bottom chart shows the temporal trends of virtual forest land use by source for major final consumers (from left to right are results for 2000, 2005, 2010 and 2015).

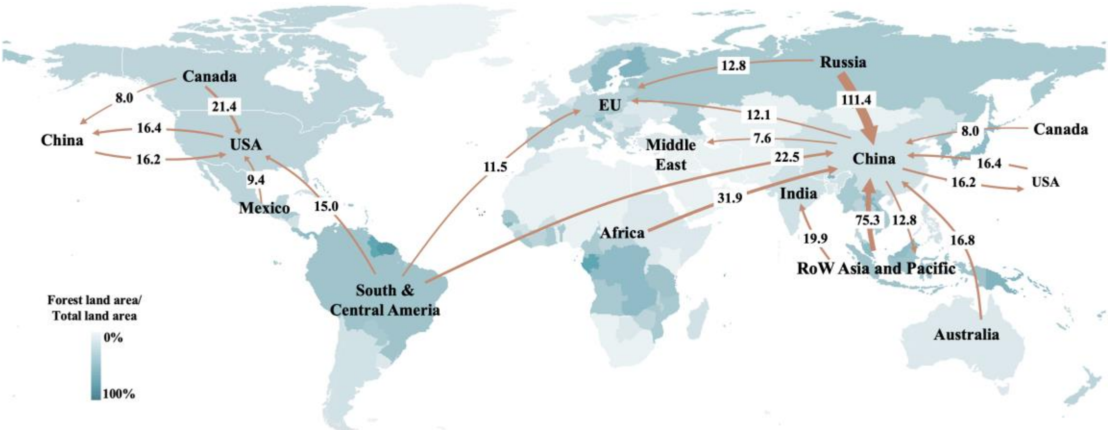
Only in Russia, Africa, RoW Asia and Pacific and RoW America, traditional primary (e.g. raw round wood and wood chips ) and processed forest products (e.g. lumber, pulp and paper) represented over 50% of virtual forest land use (89%, 82%, 59% and 54%, respectively), while they comprised a small portion in other dominant consumer countries: less than 10% in China and India and less than 16% in the USA, Indonesia and Mexico. This is because a considerable share of forest products were used as industrial intermediate input to produce other highly-processed products and to support tertiary sectors.

Fig. 1 also presents temporal trends of virtual forest land use for dominant final consumers. Generally, developed economies (including the USA, the EU and Japan but excluding Canada) witnessed decreasing consumption, but developing economies (including China, Russia, Indonesia and India) exhibited growing demand. In 2000, the USA and the EU were the top 2 final consumers (around 300 Mha each), but China and Russia took their positions in 2015. Virtual forest land use of Brazil fluctuated slightly around 150 Mha and that of Canada showed a small inverted-U shape. Moreover, the USA, the EU, China, Japan and India remained major importers during this period, and changes in virtual forest land use were mainly due to changes in import volume.

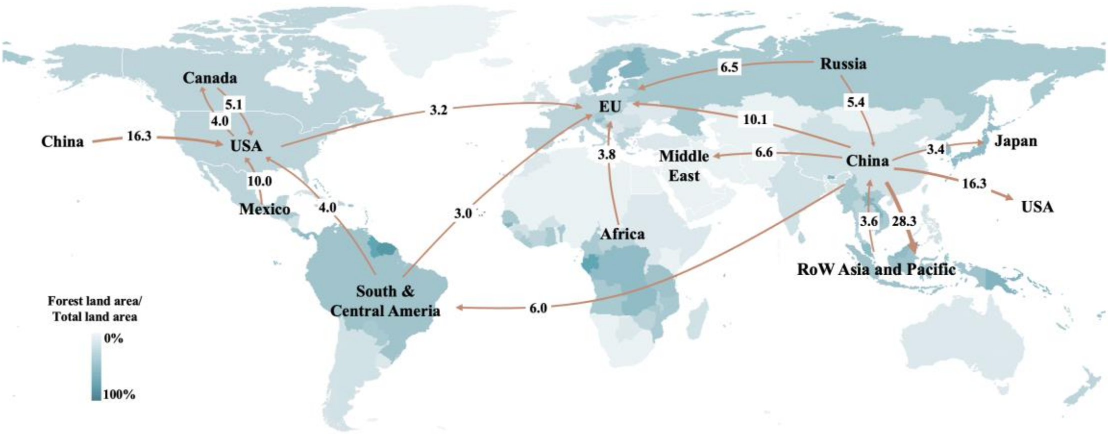
### 3.2 Virtual forest land use associated with international trade

Fig. 2 shows major trade flows in intermediate and final trade in 2015, in order to reveal how countries were interconnected in the intricate global trade network to eventually deliver finished products to final consumers. Forest land use embodied in trade among EXIOBASE 3 regions amounted to 41% of global total forest land exploitation in magnitude, with 74% arising from intermediate trade. In intermediate trade, Russia, Africa, Latin America and RoW Asia and Pacific were major exporters of forest-risk products, while China, the USA and the EU were dominant markets.

China was the largest importer with diversified trade partners: Russia, RoW Asia and Pacific, Africa and South & Central America respectively contributed 111.4 Mha, 75.3 Mha, 31.9 Mha and 22.5 Mha . Virtual forest land use embodied in the USA's import was much less than that of China, dominantly associated with export from Canada (21.4 Mha), China (16.2 Mha), South & Central America (15.0 Mha) and Mexico (9.4 Mha). Virtual forest land use linked to the EU's import derived primarily from Russia (12.8 Mha), China (12.1 Mha), and South & Central America (11.5 Mha). India was also an significant importer, with large amounts of virtual forest land use originated from RoW Asia and Pacific (19.9 Mha). Most leading importers and exporters in intermediate trade held their positions in final trade, while China turned to be the largest exporter, associated with 28.3 Mha of virtual forest land exported to RoW Asia and Pacific, 16.3 Mha to the USA and 10.1 Mha to the EU, which confirms China's role as the world factory.




(a)




(b)

**Fig. 2 Forest land use embodied in dominant trade flows in (a) intermediate trade and (b) final trade**

### 3.3 Source to sink budget

Virtual forest land traded from primary suppliers to final consumers usually flows through at least one intermediate producer. It is still unknown how much burden is put on a certain primary supplier (source) to satisfy the final consumption of a certain final consumer (sink). The source-to-sink budget is therefore required to identify the connection between source and sink regions. For EXIOBASE 3 regions, 672.6 Mha of forest land was linked to final consumption elsewhere in 2015, reaching 30% of global total exploitation. As shown in Fig. 3, 35% (142.8 Mha) of forest land exploitation in Russia was associated with export production, with China and the EU accounting for 77.1 Mha and 22.6 Mha, respectively. For Indonesia, Australia and RoW Asia and Pacific (as an aggregate region), 42% (128.1 Mha) was displaced from other regions, mainly from China (61.9 Mha) and India (19.1 Mha). The proportions for Brazil and RoW America were 28% (52.7 Mha) and 19% (42.1 Mha) respectively, with China, the USA and the EU each making up 14 Mha - 20 Mha. The ratios for Canada and Mexico reached 52% (37.4 Mha) and 28% (19.0 Mha), and the USA alone was responsible for a quarter (35.7 Mha). Forest land use displaced to Africa also reached 55.4 Mha, but only comprised 16% of local forest land use.

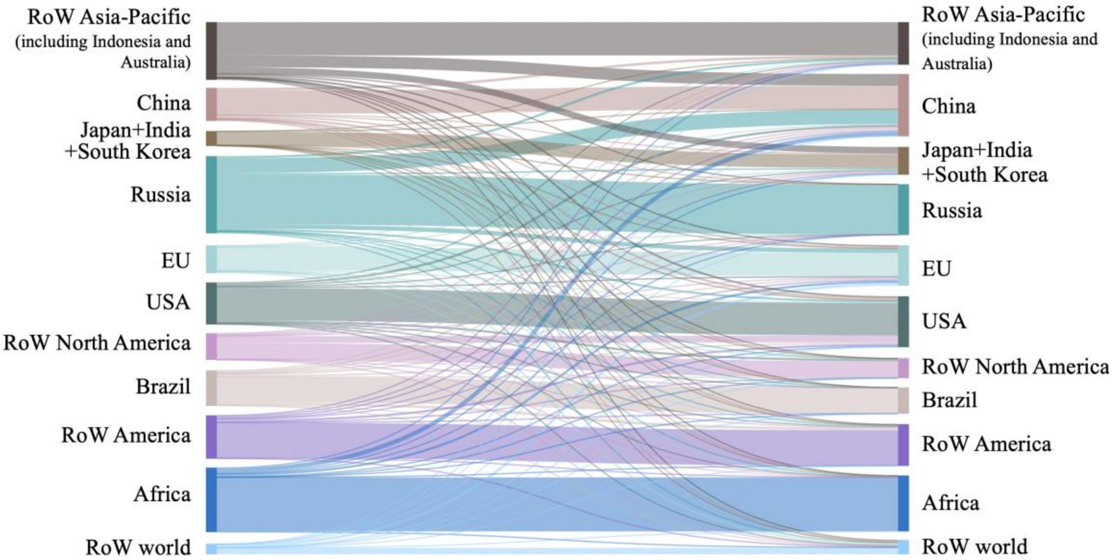



**Fig. 3 Source-to-sink budget of global forest land use**

The world is divided into 11 regions. The left side of the Sankey diagram shows direct forest land use in source regions, and the right side shows forest land use embodied in the final consumption of sink regions. The thickness of the flows (using source regions' colors) denotes the amount of forest land exploited by source regions to satisfy the final consumption of sink regions.

Forest land exploited in the regions categorized to the highest - 4$^{th}$ highest climate-vulnerable levels rose from 634.1 Mha in 2000 to 689.4 Mha in 2015, accounting for over half of total increase in global forest land use. Forest land use displaced from China to these climate-vulnerable regions rose from 24.1 Mha in 2000 to 63.8 Mha in 2015 and that displaced from India rose from 6.0 Mha to 19.5 Mha, due to escalating imports from tropical and subtropical regions (mainly Asia-Pacific). For the EU and the USA, despite the decreasing import volumes, displacement to climate-vulnerable regions remained relatively large in magnitude (21.2 Mha and 16.8 Mha, respectively). Meanwhile, for most source regions, the readiness to take adaptation actions was also low. Consequently, the proportion displaced to the least – 4th least ready regions reached 50% - 90% for the EU, the USA, South Korea and India while climbed up from 27% to 44% for China and from 30% to 51% for Japan.

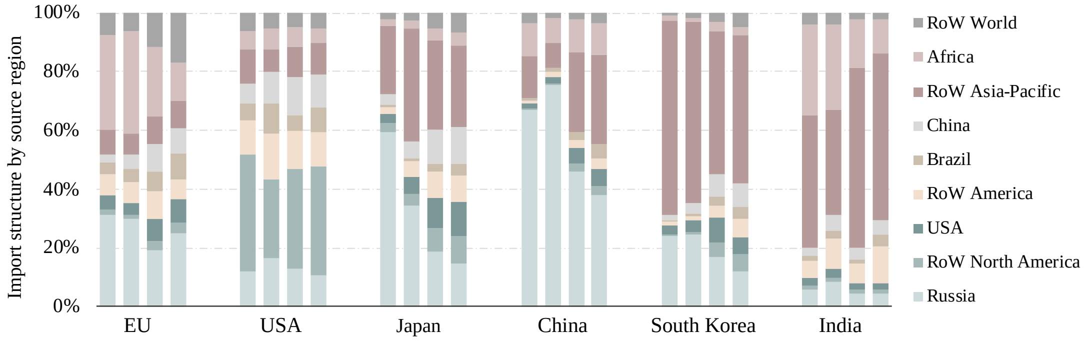



**Fig. 4 Import structure by source region for major importers in 2000, 2005, 2010 and 2015 (from left to right)**

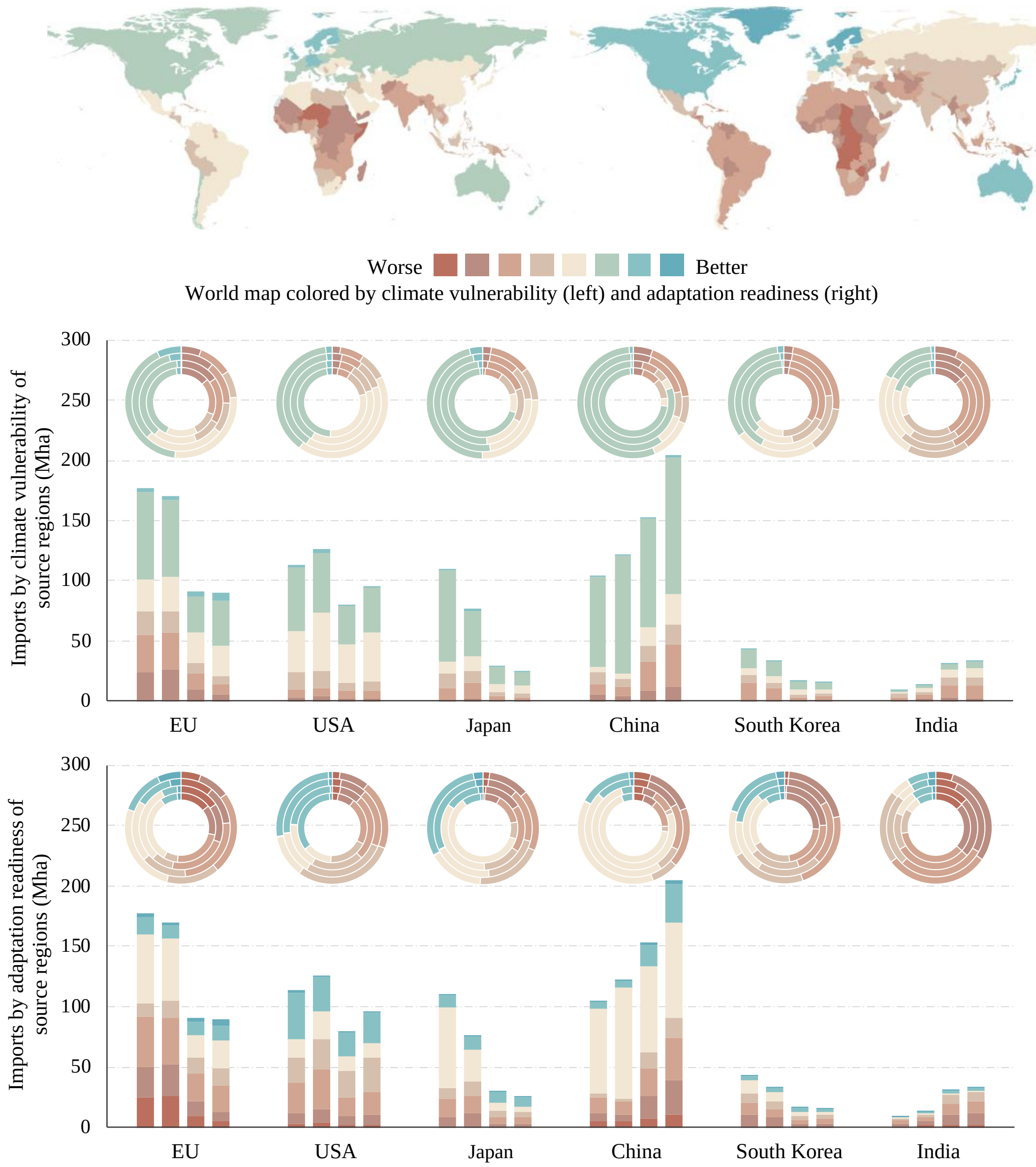



**Fig. 5 Imports by climate vulnerability and adaptation readiness of source regions for major importers in 2000, 2005, 2010 and 2015 (from left to right)**

# 4. Discussion and policy implications

The extensive displacement of forest land use reflects the globalization of forest land use facilitated by economic globalization. On the one hand, a large share of forest land use was displaced from forest-scarce places to forest-rich places or between places with different forest types. All the agents participating in the global supply chains can take what they want: importers can avoid forest exploitation and improve economic efficiency by taking advantage of high-yield and high-quality forests elsewhere, and meanwhile the exporters can gain national revenue by selling forest products. On the other hand, the land use was generally displaced from developed (e.g. the EU, the USA and Japan) and emerging (e.g. China and India) economies to developing ones (e.g. Russia, Africa, South America, South and Southeast Asia), partly because stricter standards and higher costs in high-regulating economies cause forest exploitation spillover to lower-regulating jurisdictions (Rulli et al., 2019). As a consequence, regions with high climate vulnerability and low adaptation readiness are facing growing pressure, which may exacerbate forest loss at a global scale. Actually, forestry is found to be the leading proximate cause of global intact forest loss (Potapov et al., 2017a). Even selective logging, which is often regarded as sustainable, is fragmenting the world's most precious tropical forests in the Amazon and Congo Basin (Cazzolla Gatti et al., 2015). These impacts can extend from forestry to other life-supporting socio-economic aspects. For instance, over 800 million people living below poverty line in the tropics reside around forests and savannahs, who rely on the ecosystems to meet their energy, water, nutritional, medicinal and cultural needs (FAO, 2018b; Sonwa et al., 2012). The influence can be also transmitted from producers to downstream supply chain agents. As forestry production can be highly variable in case of droughts, floods, wildfires, wind storms and insect outbreaks due to climate change (Kirilenko and Sedjo, 2007), heavy reliance on climate-vulnerable countries would pose a threat to the resilience of supply chains of forest-based products. The EU, the USA, China and India should pay particular attention, given their substantial virtual forest land import from Latin America, Africa, Southeast Asia and Oceania.

Current forest policies and programs, such as US Healthy Forests Restoration Act, Natural Forest Conservation Program of China, EU Natura 2000 and Brazilian Forest Act, mostly target on local forest conservation. However, stringent regulation in production regions restricts local exploitation without suppressing downstream demand, and the consequent supply shortage may spark illegal exploitation and trade, while forest protection in consumption regions alone may aggravate land use displacement. Therefore, transnational joint efforts are needed to ameliorate negative impacts caused by land use globalization. From one aspect, deforestation and forest degradation from land use should be mitigated. Given economies are connected through international trade, market-oriented approaches can be adopted. Production regions can impose taxes on exploiters for ecosystem services loss and carbon emissions, so that environmental and ecological externalities can be internalized. The tax can be also earmarked for sustainable forest management specifically. Dominant final consumers, such as the USA, China, the EU, Japan and India, can adopt forest certification, which promotes management of distant forests by informing consumers whether the production process conforms to certain standards and thus helping weed out products that are not eco-friendly (Villalobos et al., 2018). From another aspect, it is imperative to help climate-vulnerable producers to adapt to climate perturbation. Developed economies can share successful forest management experiences and technologies, such as fire controlling via regulation and education and satellite-based monitoring system that can guarantee traceability (Gralewicz et al., 2012; Verhegghen et al., 2016). It is also helpful to provide experiences of enhancing institutional and society arrangement that can effectively leverage investments for adaptation actions, since insufficient financial resource is a major barrier to forest management in many regions (Malhi et al., 2008). For example, recent years have witnessed surging foreign investments in Africa (Conigliani et al., 2018), then the market forces can be directed to improve local adaptation capacity in case of climate disruption. Moreover, in order to strengthen supply chain resilience, consumers can diversify or reduce reliance on imports, especially those from climate-vulnerable regions.

Above discussions of forest land use are from the perspective of forests' provision of ecosystem services and material resources, while forest land also serves other socio-economic functions, such as creating national revenue. According to the World Bank, forest rents contributed 2.4% of GDP in Sub-Saharan Africa in 2011 and the ratio was even higher in individual African countries (WB, 2018). To preliminarily measure the economic efficiency of forest land use, an indicator termed as forest land productivity is constructed, with reference to the indicator "resource productivity" adopted by OECD (OECD, 2011). It is calculated as monetary trade volume divided by forest land use embodied in corresponding trade flows. As shown in Fig. 6, forest land productivities associated with export of most production regions were low, reflecting their specialization in low value-added segments of global supply chains. Poor economic return may stimulate more forest exploitation, which in turn impairs land productivity and leads to a vicious circle. Hence, these regions should expand capacity to add value to forest-risk products, gradually getting rid of the so-called resource curse. Moreover, there may be conflicts between eco-environmental and socio-economic functions of forest land. For example, forestry can trigger negative environmental impacts, while strict logging prohibition may cut off the already pitiful income of local residents. The uneven distribution of gains and losses will further lead to social inequality and instability. Therefore, future work should pay more attention to the synergies and trade-offs between multiple functions of forest land.

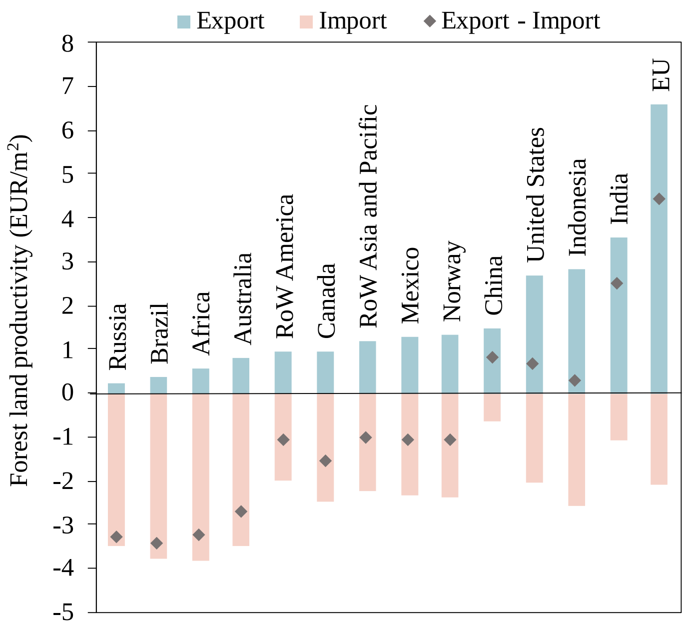



**Fig. 6 Forest land productivity associated with import and export for dominant supply chain agents**

Our results also have academic implications regarding the accounting of virtual forest land use. A substantial share of forest land use was associated with the final consumption of non-forest products. In other words, countries can make use of foreign forest land even without importing traditional forest products. Conventional trade balance analyses of only forest products will overestimate forest land use driven by manufacturing countries (usually developing countries) while underestimating that of actual final consumers. Given the growing awareness to adopt consumption side policies and supply chain initiatives, it is necessary to identify the real end users and reveal their roles in driving forest land use. Due to the intricate international trade network, it is increasingly difficult to trace forest land use through the entire global supply chains with tools based on physical trade flows. The embodiment accounting that inclusively covers all the trade flows can provide complementary information to existing analyses that only consider traditional forest products.

**Limitations and future perspectives**

Data on direct forest exploitation have uncertainties. There is no agreed-upon definitions of forests. For example, FAO defines forest land as an area more than 0.5 hectare with trees higher than 5 meters and tree cover greater than 10% (FAO, 2010; Schepaschenko et al., 2015), while others set a threshold of 20% (Potapov et al., 2017b) or 25% (Pendrill et al., 2019). This may lead to the discrepancies in the findings of different studies. There are also limitations in input-output analysis resulting from the compilation of input-output tables. Due to the regional aggregation in EXIOBASE 3 input-output tables, forest land use displaced via international trade is underestimated.

It is also hard to identify the actual importers and exporters at a subnational scale. Physical and hybrid accounting are alternative tools. However, physical accounting has limits in identifying the origin and end users and there are large uncertainties to convert yield of forest products to actual land use (also the problem of hybrid approach that combines IOA and physical accounting) (Bruckner et al., 2015; Weinzettel et al., 2013). Since this paper focuses on the displacement of forest land use, the capability of input-output analysis to trace forest land use from the origin to the end is especially important to us. Considering current data availability and technical feasibility, analyses with different methods and diverse focuses are essential to provide complementary information.

Meanwhile, several problems remain to be solved in the future. First, it would be better to consider the heterogeneities of forest land in terms of productivity, vegetation type, carbon sequestration, biodiversity conservation and other ecosystem services. Since the concept of forest used in the present and most previous papers includes all the areas that meet certain thresholds which wipes out the heterogeneities of forests, it is hard to tell exactly whether the transfer of forest land use bring about net gains or net losses from different perspectives. Consequently (Second), future analyses should not be limited to land itself but investigate multiple consequences of forest land use, such as changes in biodiversity and carbon stock due to land use displacement. Third, more efforts are needed to improve the region resolution of forest land analysis. This paper conducts the virtual land accounting at the expense of limited region details, which hinders more detailed analyses for individual countries. Scholars in different fields are encouraged to strengthen communication and cooperation in order to develop methods and databases that are more suitable for research with different purposes.

## Conclusions

This paper provides a comprehensive overview of forest land use across global supply chains for the world economy by means of embodiment accounting based on the data provided by EXIOBASE 3. A specific focus is put on the climate vulnerability and adaptation readiness of supply chain agents, based on Notre Dame Global Adaptation Index (ND-GAIN) Country Index.

2268.3 Mha of forest land was exploited for forestry in 2015, with China as the leading final consumer of virtual forest land use (325.7 Mha), followed by Africa (292.7 Mha), Russia (266.4 Mha), the USA (266.1 Mha), RoW America (218.8 Mha) and Brazil (138.1 Mha). For EXIOBASE 3 regions, 30% (672.6 Mha) of global total forest land use was linked to export production. For Russia, the largest exporter, 35% (142.8 Mha) of forest exploitation was embodied in export, with China and the EU accounting for 77.1 Mha and 22.6 Mha, respectively. The proportions for other major producers ranged between 16% (Africa) - 52% (Canada), respectively. Developed economies (including the USA, the EU and Japan but excluding Canada) generally decreased virtual forest land import, but China and India showed growing reliance on the tropical and subtropical regions (especially in the Asia-Pacific), which are vulnerable to climate change and have low readiness to take adaptation actions. At a global scale, increasing forest land was exploited in climate-vulnerable regions, contributing over 50% of the total increase in global forest land use.

Therefore, transnational joint efforts are needed to ameliorate negative consequences caused by forest land use displacement. On the one hand, forest loss following forest land use should be mitigated, for example, through ecological payments, carbon tax and forest certification. On the other hand, consumer countries should help climate-vulnerable source countries to adapt to climate disruption, for example, by sharing experiences and techniques to monitor and control climate disruption and to enhance institutional, society and economic environment for adaptation actions. Furthermore, synergies and trade-offs between the multiple functions of forest land in eco-environmental and socio-economic systems should be considered.

## Declaration of interests

The authors declare no competing interests.

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