Mapping the deforestation footprint of nations reveals growing threat to tropical forests

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Deforestation, a significant threat to biodiversity, is accelerated by global demand for commodities. Although prior literature has estimated the global supply chains, here we provide a fine-scale representation of the deforestation associated with international trade. Using remote sensing data and a multi-region input-output model, we quantify and map the spatial-temporal changes in global deforestation footprints over 15 years (2001-2015) at a 30-m resolution. We find that tropical deforestation is growing, while hotspot deforestation is decreasing. We also find that the deforestation embodied in their imports, of which tropical forests are the most threatened biome. Consumption patterns of 47 countries drive an average loss of 3.9 trees per person per year. Some of the hotspots of deforestation embodied in international trade are also biodiversity hotspots, such as in Southeast Asia, Madagascar, Liberia, Central America and the Amazonian deforestation. Our results emphasize the need to reform commodity supply chains and improve supply chain transparency, public-private engagement and financial support for the tropics.

Forests are the dominant terrestrial ecosystem, covering 30.6% of the global land area in 2015. They are not only home to many species on Earth but are also of significant importance to human wellbeing by providing invaluable ecosystem services. Among forest biomes, tropical forests stand out as the richest biodiversity ecosystems, harboring 50-90% of all terrestrial species. Despite accounting for only 6% of the total tropical forest area worldwide, mangroves (groups of trees in tropical and sub-tropical tidal areas) create habitats for a variety of animal species, especially marine mammals.

It was reported that the world’s forest area has been declining annually over the last 25 years. Deforestation, which has become a major global concern, contributes largely to anthropogenic greenhouse gas emissions, biodiversity loss and changes in the hydrological cycle. Over half of Earth’s remaining tropical rainforests are located in the Amazon Basin, where the deforestation rate has increased since 2013[1]. Local use of fire to illegally clear forest areas to be used for crops (mainly soybean) and cattle grazing[2]. Under the efforts of Jair Bolsonaro’s government to weaken forest conservation, commercial deforestation and land development, the number of forest fires and deforestation has increased sharply in the Brazilian Amazon since 2019[3].

Economic development and international trade are considered main driving forces of deforestation[4], which has been driven by commodity production, forestry, agriculture and urbanization, among others[5]. The relationship between forest degradation and international trade and forest commodities has been confirmed in the literature[6].

Many developed countries, such as the USA, Japan, Germany, France, the UK, and Italy, and several developing countries, such as China and India, have obtained net domestic forest gains[7]. The net forest gains made in these countries were partially offset by importing embodied deforestation from elsewhere[8]. However, the spatial distribution of deforestation embodied in imports has not been dealt with in depth. Furthermore, while several studies have analyzed the deforestation induced by the production and exports of forest-risk commodities, these analyses either focused on selected tropical countries with high deforestation rates[9], or used outdated deforestation data[10]. Overcoming these problems, Pendrell et al. recently quantified deforestation (based on new avoidance forest loss data) as being associated with the expansion of agriculture and forest plantations across the tropics and sub-tropics[10]. In spite of that, they used an assumption-based simple land balance model that did not consider land use changes. Our analysis was conducted by Zhang et al. at the global scale, but it only captured timber harvest footprints and could not identify the deforestation footprints due to agriculture and other sectors[11].

Thus, previous works were limited to non-structural estimations of embodied deforestation, either from several forest-risk commodities or within the tropics and sub-tropics, while the global deforestation embodied in international trade has never been fully mapped.

As such, tracing the spatial patterns of the deforestation footprint enables better identification of deforestation dynamics, which can lead to a more effective approach to reducing the ecological impacts of global deforestation in general and forest clearance at biodiversity hotspots in particular. Using high-resolution forest loss data[12], we perform a real spatial classification of deforestation drivers and a detailed global supply chain analysis[13] (Fig. 1 and Methods section), we thus present a mapping-based comprehensive synthesis of the international trade driven the spatiotemporal changes in global deforestation over 15 years. Our analysis addresses two main questions: (i) Which deforestation hotspots are driven by which consumer countries? and (ii) Which forest ecosystems, tropical rainforests or other forest types at the top targets of global supply chains?

Results

To build high-resolution maps of the deforestation footprint of various nations, the global forest loss (presented by Landsat imagery based maps developed by Hansen et al.) was linked to the yearly global supply chain model during 2001-2015. While there are multiple coexisting concepts and definitions of deforestation[13], within the context of this study, we use the term deforestation to refer to the forest loss in Hansen’s data, where deforestation includes both short- and long-term losses of forest cover. Forest loss is subsequently defined as complete removal of tree cover exceeding 5 m in height (in year 2000) at the Landsat pixel scale[14]. Only forest loss associated with the dominant anthropogenic activities—(i) which are agriculture, forestry, urbanization and production of other commodities, which was used in the mapping. The Hansen data also include removal plantations[15], we exclude tree plantations from the deforestation calculation by developing a spatial plantation mask layer (see Supplementary Appendix 1 for details). While we acknowledge the uncertainty of the deforestation footprint maps, attribution of forest-forest to deforestation drivers, which is based on spatially explicit data, allows us to locate the potential deforestation footprints at a pixel level. Because our analysis does not trace the subsitutional supply chain, it is not possible to accurately link deforestation in one subnational area to consumption in each country.

In general, we find that the main trading partners implicated in deforestation footprints include many tropical countries, such as Brazil, Madagascar, Argentina, Indonesia and Côte d'Ivoire. These countries majorly export forest-risk commodities (for example, cattle, soybeans, coffee, cocoa, palm oil and timber) to the EU countries and China (based on consumption and sourcing patterns, the spatial coverage of deforestation footprints and location of potential deforestation hotspots vary between countries. Figure 2 shows the 15-year cumulative spatial deforestation footprints of the USA, China, Japan, Germany (the world’s four largest economies), Singapore (an Asian Tiger) and Brazil (with the largest tropical rainforest area). Given the small population size, the deforestation induced by Singaporean consumption mainly occurs in countries throughout Southeast Asia (especially in Peninsular Malaysia and Singapore) and some unexpected footprints in eastern Madagascar and the Petén region of northern Guatemala. Conversely, Brazil has primarily driven domestic deforestation along with footprints in the Gran Chaco region (northern Argentina and western Paraguay), and several other countries. The maps of the largest economies clearly confirm that international trade is associated with global deforestation. China, Japan and Germany have similar spatial patterns of deforestation footprints that spread at the tropics (from Southeast Asia to West Africa and throughout the Amazon rainforest) and also cover Southern China, the southern USA, Central America, Northern Europe, Portugal and parts of Brazil in North-eastern Brazil, and Northern Europe. Besides, the deforestation footprint maps are most significantly reduced at the EU countries (especially France and Germany), and Brazil demonstrates that deforestation is more important for deforestation in Indochina—particularly in northern Laos for timber and rubber.

The US footprint is clearly distinguishable from those of the countries listed above, with US consumption leading to higher deforestation in various deforestation hotspots (see Supplementary Video for details). These hotspot countries include central Cambodia, eastern Madagascar, Liberia, Central America (the Petén Basin of Guatemala, eastern Honduras and central and eastern Nicaragua), southern Chile and southern Amazon rainforest (where agriculture and grazing are extensive in the Brazilian Highlands and northern Argentina). The USA became the main importer of a wide range of commodities from these tropical countries, for example, timber from Cambodia, rubber and related products from Liberia, edible oils and fruits and nuts from Guatemala and soy and beef from Brazil. We also observe a high US deforestation footprint in Canada as a result of the US being the primary export destination for Canadian forest products, of which a certain proportion is sourced in the USA.
Fig. 2 | Global deforestation driven by consumption in six example countries. a-f. Maps of cumulative spatial deforestation footprint over 15 years, from 2000 to 2015, for China (a), Brazil (b), Germany (c), Singapore (d), Japan (e) and USA (f). The pixel values is the percentage of embodied deforestation by the largest consumer country within the pixel area. All maps are rescaled for display purposes from the 30 m resolution to the 0.002° pixel size. Higher-resolution maps are provided in Supplementary Fig. 6.

The degree of deforestation footprints also vary by different deforestation drivers at the sub-national level. For instance, coffee imports in the USA, Germany and Italy induce dramatic deforestation in the Central Highlands of Vietnam, while timber exploitation in North Vietnam mainly exports to China, South Korea and Japan. In Brazil, timber products from Mata Atlantica are mostly consumed domestically. However, consumption across the EU-27 nations and USA-China drives deforestation in the Amazonia and Cerrado biomes of Brazil for soy and beef. Japan’s timber consumption poses the highest risk to the forest in Sarawak (a Malaysian state on Borneo) while China shares the most significant responsibility for deforestation across the country (from Peninsula Malaysia to East Malaysia) because of the imports of agricultural commodities, such as oil palm, rubber and cocoa.

Using the high resolution deforestation footprint maps shown in Fig. 2, we produced country profiles for the temporal trends of the deforestation footprints (Fig. 3a). Despite the growing recognition of the seriousness of deforestation in developing countries, deforestation footprints have remained largely unchanged. While forest restoration can reverse the effects of deforestation, our maps cannot integrate both dimensions, that is, forest loss and gain, into deforestation footprints because of the lack of yearly forest gain in the data. To deepen our understanding of the relationship between deforestation footprint and forest restoration, we quantitatively and compare forest cover and international trade-adjusted forest cover changes in five groups (Fig. 3b). These groups consist of the G7 members, two green leaders [China and India], three tropical countries (Brazil, Indonesia and Mexico), the remaining G20 countries, and non-G20 countries. Generally, between 2000 and 2015, we found either increases in forest cover or decreases in net forest loss in all groups. However, while abolishing net forest gains, China, India and the G7 countries (except for Canada, in which forest cover is decreasing) have increased the deforestation footprints outside their borders. As such, China and India have been expanding their footprints rapidly. In 2014, the deforestation embedded in imports of both countries was more than six times those of 2001. Brazil, Indonesia, Mexico and the non-G20 countries (which also include many tropical nations) reduced their net forest loss more slowly than they have increased their international trade-adjusted forest cover changes. This gap is the result of hosting the additional international trade-adjusted forest cover changes of China, India and the G7 countries. The remaining G20 countries obtained both net forest gains and positive international trade-adjusted forest cover changes from 2006 onwards but had decreased their international trade-adjusted forest cover in 2015, see Supplementary Fig. 3 for detailed information on each G20 country.

We expanded the above analysis of deforestation footprints by examining the number of tree loss (Fig. 3c) and deforestation area embodied in per capita consumption (Fig. 3d). These figures only show the absolute tree forest losses without compensating for tree forest restoration. The tree loss per capita for each country was estimated by combining our global level deforestation footprint maps with a global tree density map. Residents in the G7 countries drove an average loss of 4 trees or 25 m² of forest per person through their consumption in 2015. Although the deforestation embodied in Singapore’s imports is concentrated in Southeast Asia, the impact of Singapore’s imports was slightly higher than that of the average American, who was responsible for five trees being lost in 2015 (Fig. 4f). The average tree loss per capita in Japan, Germany, France and the UK was similar, at around half of that in the USA. While Swedish consumption induces an average loss of 2.2 trees per person (mainly because of biomass use, which represents 22% of the national energy supply, for the generation of electricity and district heat), that in Norway and Canada was around 16, China and India registered values below 1. However, these differences do not reflect the responsibility of each country’s citizens regarding global.
biodiversity threats and climate change because different tree types may have different environmental and ecological roles. For example, the environmental impact of three Amazon rainforests used by a Brazilian might be more severe than the impact of 14 cultivated trees due to the use of a Norwegian citizen in temperate and boreal biomes. Because tree densities are not distributed equally among forest biomass or geographically, the per capita deforestation footprint ranking differs between the two measurements based on the number of tree loss or the deforestation area.

As such, it is crucial to quantify biome-level deforestation footprints in addition to the global-level maps. The biome-level deforestation footprint is calculated by combining spatially explicit data of the global-level deforestation footprint and a map of biome distribution. We classified the deforestation footprints into six forest domains, namely Mediterranean forests growing under Mediterranean climate zones that cover not only the Mediterranean Basin, mangroves, tropical, temperate, boreal and other forest types. Based on the spatial correlation dataset prepared by the Nature Conservancy (http://maps.bsc-ibc.org). Here, the tropical biome includes forests in the tropics and subtropics, except for mangroves. While deforestation countries and China have become major net importers of tropical deforestation-related commodities, developing countries in the tropics, such as Brazil and Indonesia, are major net exporters (Fig. 4). Several countries play both roles, that is, as net importers and exporters. The USA is a net exporter of temperate deforestation-related goods and a net importer of other goods related to deforestation. Russia imports tropical deforestation-related products, but domestically driven boreal deforestation linked to export production. Tropical forests are the most threatened by supply chains in many countries. Although the USA, Japan, Germany, Singapore, China and Russia increased their net forest imports from all biomes in 2015, compared with 2001, the imports of tropical deforestation-related commodities increased significantly (Fig. 4). Being the main net importers, the rate of tropical forest products in the non-domestic embedded deforestation of these countries reached maximum values of 74% and 77% in 2011 and 2015, respectively. For 47 countries, that is, Japan, Germany, France, the UK, and Italy, they have 91–99% of their deforestation footprints in foreign countries, of which 49–57% was tropical deforestation in 2015. The amount of tree loss and deforestation area per biome embodied in per capita consumption can be found in Extended Data Fig. 1.

The deforestation footprints are further examined per unit of gross domestic product (GDP). The demand for wood and oil products is pushing the expansion of croplands, pastures and forestry in tropical countries. The relationship between GDP per capita and the percentage of tropical forest/mangroves in the total embedded deforestation per G20 country is shown in Fig. 5b. Although tropical rainforest deforestation driven by developed countries' consumption is obvious and most developed countries drastically increased their GDPs per capita from 2001 to 2015, these nations have not changed their international trade patterns, thus their tropical forest dependence has continuously increased, except for certain countries, such as Norway and Sweden. The decoupling between economic growth and the tropical deforestation footprint occurs for the net exporters of tropical deforestation-related commodities, such as Brazil and Indonesia. In this way, it may simply indicate that these countries met their demand by increasing imports of foods, goods and services. Further, China and South Korea recently reduced their mangrove deforestation footprints, while G7 countries maintained the embodied mangrove deforestation at levels similar to those of tropical deforestation (Fig. 5b). Consequently, while G20 countries are still dependent on tropical forests and mangroves, economic growth does not solve the embedded deforestation in the tropics and subtropics.

**Discussion**

We produced a fine-scale spatiotemporal continuous maps of deforestation footprints of nations. These maps can help better understand the deforestation dynamics embodied in international trade chains. Understanding global deforestation footprints is essential to create better regulatory policies and science-based interventions for protecting forests in various hotspots. Using the maps, we determine which consumer countries have driven deforestation in various ecosystems and producer countries. For many developed countries, their commodity consumption, such as beef and soybeans, induces more deforestation beyond domesticity. This finding is similar to the biodiversity loss embodied in the international trade, the major which occurs outside the territorial boundaries of exported economies. Since deforestation is an important driving force, our maps can help policymakers select species hotspots that can be prioritized by a specific country for reducing the ecological impact of its deforestation footprint. By combining the spatial patterns of deforestation with biodiversity footprints, global policies for reducing the impacts of international trade on nature can be considered in the context of shared benefits for both forest biodiversity conservation.

**Our results indicate that to maintain net forest gains, China, India, the G7 countries and other developed countries have mostly expanded their non-domestic deforestation footprints in forest biomes, among which tropical forests prevailed. The trend seems to be increasing, while the global deforestation rate is still decreasing.** It is well known that tropical forests stand out as the richest biodiversity ecosystems among forest biomes, absorb a vast amount of carbon dioxide and are suppliers of many ecosystem services. Some identified deforestation hotspots embedded in international trade are also biodiversity hotspots, such as the Amazonian rainforest, which leads to significant conservation concerns. Because the biodiversity value of tropical primary forests is irreplaceable, an urgent task for conservation is to reduce tropical deforestation induced by national consumption and international trade.

Our analysis has some limitations associated with deforestation driver classification and input data. First, the drivers of global forest loss were originally classified into five types: commodity-driven deforestation, shifting agriculture, forestry, wildlife and urbanization. Wildlife was not included in our analysis because it was defined as large-scale forest loss resulting from burning with no visible human activity afterwards. As we cannot quantify the contribution of shifting agriculture in international trade, this driver merged with long-term agriculture, mining and energy infrastructure and included in commodity-driven deforestation. Accordingly, we considered the global supply chain through three drivers (forestry, urbanization, and agricultural and other commodities), which may overestimate deforestation for the agriculture sector.
Second, deforestation drivers, which are complex and can change rapidly, are difficult to identify accurately in detail. As such, the deforestation driver we used is novel but has a coarse resolution of 10-km x 10-km grid cell. The incompatibility between the resolution of the two data layers, that is forest loss at the 0.5-m observation scale) and deforestation drivers, could lead to an overestimation of factors such as urbanization-related deforestation or to the misallocation of embodied deforestation to a wrong location around the boundary. Third, it is essential to highlight that we do not localize the magnitude of embodied deforestation for each deforestation driver at the subnational level for a few reasons; for example, our analysis cannot distinguish where agricultural production contributes to exports because of the different proportions of a commodified agricultural commodity (e.g., maize from Iowa) present in each country. Therefore, a map piece has a mean value of deforestation driven by a consumer country over the entire producer country per deforester. This bias level of deforestation deforesters, which can be embodied in a country can be concentrated at one biome more than other biomes within a producer country.

Despite these limitations, our study depicts the global deforestation drivers. Understanding the deforestation embodied in global supply chains can help to create better regulatory policies and science-based interventions for protecting the forests in numerous hotspots. Public awareness of combating tropical deforestation has been increasing, along with the creation of many zero-deforestation pledges in three main governance areas from governments, companies, and international organizations. Reducing deforestation is a key policy to fight Forest Degradation (RFDD+) and sustainable supply chain initiatives. However, the funding available to secure these agreements has not been adequate, and deforestation remains a serious problem. By determining the drivers of deforestation and measuring the embodied deforestation in global supply chains, we observe that the effectiveness of ETS certification for halting deforestation remains uncertain. The current ETS system may not be enough to address the scale of deforestation and forest degradation. The recognition of deforestation drivers may help to identify and modify the actual drivers, reduce the level of deforestation, and provide a better understanding of the drivers to aid in the reduction of deforestation.

In this study, we estimated the true deforestation driven by the global supply chain (Fig. 3B) by linking deforestation data and country-level deforestation drivers. The results show that deforestation drivers are complex and influenced by multiple factors. We also found that deforestation drivers are not only driven by the direct impact of deforestation drivers but also by their indirect impacts, such as the indirect impact of deforestation drivers on deforestation drivers through the supply chain. This finding suggests that to reduce deforestation, it is important to consider both direct drivers and indirect drivers, such as deforestation drivers in the production and consumption of other products. This finding has important implications for deforestation drivers in the international trade, which can be used to reduce deforestation drivers in tropical forests and forest degradation, and the need to reduce deforestation drivers in the future. The results also suggest that the effectiveness of ETS certification is not enough to address deforestation drivers and that more comprehensive measures are needed to address deforestation drivers in global supply chains. Therefore, it is important to consider both direct drivers and indirect drivers, such as deforestation drivers in the production and consumption of other products, to reduce deforestation drivers in global supply chains.