Risk of intact forest landscape loss goes beyond global agricultural supply chains

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Summary: The continued loss of unfragmented intact forest landscapes (IFLs) despite numerous global conservation initiatives indicates the need for improved knowledge of proximate and underlying drivers. Yet the role of non-agricultural activities in forest degradation and fragmentation has not received adequate attention. We focus on IFL loss caused by various economic activities and investigate the influence of global consumption and trade via the multi-regional input-output model. For IFL loss associated with the 2014 world economy, over 60% was related to final consumption of non-agricultural products. More than one-third of IFL loss was linked to export, primarily from Russia, Canada and tropical regions to mainland China, the EU and the USA. Of IFL loss associated with export, 51% and 26% was directly caused by logging and mining/energy extraction, respectively. The dispersed nature of IFL loss drivers and their indirect links to individual final consumers call for stronger government engagement and supply-chain interventions.

Introduction

Intact forest landscapes (IFLs), defined as continuous expanses of forests and associated ecosystems detecting no evidence of human interference and having sufficient space to maintain native biodiversity (a minimum size of 500 km^2) [1], play an irreplaceable role in delivering ecosystem services, such as regulating climate [2,3] and harboring biodiversity [4,5]. For example, IFLs have higher resilience to natural disturbance (e.g., climate change) and store much more carbon per hectare than other forest zones (over 3 times higher in Latin America and Africa) [1]. Boreal IFLs also contain a large fraction of Arctic permafrost, which is a crucial organic carbon reservoir [6]. Possibly due to insufficient knowledge of both proximate and underlying drivers of IFL loss, global IFL area reduction has reached 1.5 million km^2 during the last two decades, more than quadruple the area of Germany. Only 20% of the global tree cover was within IFLs by 2020 [7]. Carbon emissions from IFL loss may compromise global net-zero strategies and hinder the implementation of land-based climate solutions.

There is widespread concern about the driving effects of local production on deforestation. Agricultural expansion as the primary proximate driver of deforestation has been well acknowledged and broadly studied [8]. However, regional land use change is no longer simply driven by local demand, but is rather indirectly influenced by international markets and the surging consumption of land-based products [9]. Countries with forest conservation goals can import finished land-based products via global supply chains, displacing land-use pressure and related eco-environmental impacts outside their own territory borders. For example, Russia produces large amounts of wood for forest-scarce or strictly regulated regions (e.g., China and the EU), which puts pressures on Russia's domestic IFLs [10]. Such globalization of land use has spurred substantial studies on consumption-side drivers of land use [11,12], deforestation [13,14] and corresponding environmental impacts [15,16], but none have focused specifically on IFL loss.

In addition to deforestation (i.e., the complete removal of tree cover followed by a change in land use), forest ecosystems are also facing emerging threats from degradation and fragmentation. Even the removal of narrow tracts of forests can affect overall forest structure and composition, inducing landscape-scale ecological changes (e.g., tree mortality and biodiversity loss) [17,18], increasing vulnerability to external disruption (e.g., fires and wind) and initiating a cascade of land use changes because of easier access to the remaining forests [19,20]. Forest degradation and fragmentation caused by logging sites and roads often precede deforestation [21]. In particular, mining and energy extraction has become a dominant culprit second only to agriculture, due to fragmenting effect of narrow exploration trails and electricity transmission lines [22]. Carbon loss resulting from forest degradation has also exceeded that from deforestation in the Brazilian Amazon [23].

Since the framework of IFL mapping emphasizes the critical role of forest intactness and size, degradation and fragmentation from forestry, mining and energy extraction can receive due attention. For example, an 800 km^2 of primary forest that is bisected by a road into two tracts less than 500 km^2 each would be identified as 800 km^2 of IFL loss. There can also be IFL loss with no or little deforestation, if primary forests are replaced by planted forests. As the trade of industrial roundwood, fossil fuels, metal and minerals represents a large portion of global total production [24-26], tele-connecting regional IFL loss to distant consumption can provide a novel perspective of how global supply chains of various non-agricultural commodities influence worldwide forest ecosystems. Considering the exceptional conservation value of IFLs in terms of stabilizing terrestrial carbon stocks and harboring biodiversity, IFL loss displacement can also reflect potential indirect driving forces behind carbon emissions and biodiversity loss.

Given all this, we provide a comprehensive overview of IFL loss associated with global supply chains, with a specific focus on the distinct roles of various economic activities as well as their links to domestic consumption and export production. To do so, we integrate a spatially-explicit global dataset on IFL loss with the multi-regional input-output model based on the Global Trade Analysis Project (GTAP) database [27]. Our results show that, for IFL loss associated with the 2014 world economy, 37% was related to export production destined for global markets, especially mainland China, the EU and the USA, of which over three quarters was directly caused by logging, mining and energy extraction. More than 60% of the overall IFL loss was linked to the final consumption of a highly dispersed range of non-agricultural commodities, with indirect links to individual final consumers. Therefore, distinct from agriculture-dominated deforestation, tackling IFL loss requires stronger engagement of national governments complemented with supply-chain and demand-side interventions.

Results

IFL loss embodied in final consumption

The global dataset classified IFL loss into 5 proximate causes, including wildfires, industrial logging, agricultural expansion, mining/oil and gas/hydropower as well as transportation for other aims, and we only considered IFL loss caused by human economic activities (excluding wildfire). Of all the anthropogenic IFL loss, industrial logging, agricultural expansion and mining/energy contributed 47%, 35% and 15%, respectively. IFL loss is accordingly allocated to the primary economic sectors directly responsible for the loss and then traced through downstream intermediate producing sectors (which use primary products as intermediate input) eventually to the final consumption of IFL-risk final products.

Fig. 1 presents the IFL loss associated with the final consumption of six region groups (consistent with World Bank definitions) and dominant final consumers. Most of major producer and consumer countries are listed in the GTAP database, but the Democratic Republic of the Congo, Gabon and Republic of the Congo, which are among the top 10 countries with the most widespread IFL loss, are aggregated to South Central Africa or Rest of Central Africa. At a national scale, the attribution of embodied IFL loss was dominated by hotspots of IFL loss (see Fig. 2) as well as large consumer countries. Brazil was the largest final consumer of IFL-risk products (related to 0.92 Mha of global IFL loss, 16%), followed by Russia (0.59 Mha, 11%), mainland China (0.57 Mha, 10%), the USA (0.31 Mha, 6%), Canada (0.28 Mha, 5%), Bolivia (0.27 Mha, 5%), Peru (0.24 Mha, 4%), Indonesia (0.23 Mha, 4%) and South Central Africa (0.20 Mha, 4%). The embodied IFL loss of other countries and regions was less than 0.20 Mha. For the six region groups, Latin America accounted for the largest share of embodied IFL loss (35%), mainly due to extensive IFL area reduction locally. Asia-Pacific and Europe & Central Asia accounted for approximately 24% and 19% respectively, as a combined result of the high consumption level of developed and emerging countries and large-scale IFL loss in a handful of countries within these regions (e.g., Indonesia and Russia). Only 10% of global IFL loss was associated with the final consumption of Sub-Saharan Africa.

When linking proximate causes of IFL loss to final consumption sectors (Fig. 1D), it can be observed that, IFL loss from agricultural expansion was primarily associated with the final consumption of food, but considerable logging- and mining/energy-driven IFL loss was embodied in construction, tertiary and other secondary sectors. This means that some of the primary products from logging and mining/energy (e.g., roundwood and crude oil) were used by these sectors as intermediate inputs to produce final products and support services. Overall, only 39% of IFL loss was linked to agriculture-related products (including primary and processed food, textiles and wearing apparel), while 18% was linked to forest, metal, mineral and energy products and the rest to services and highly processed products.

The final consumption sectors associated with IFL loss varied greatly across countries and regions. In Latin America, 68% of IFL loss was embodied in the final consumption of agriculture-related products, while raw forest products, timber and paper took the lead in South Central Africa (56%). A notable share of IFL loss was embodied in construction in Indonesia (49%), mainland China (45%), Canada (36%), Cameroon (31%), Japan (27%), India (25%) and Russia (21%), and final consumption of mineral, metal and energy products represented a relatively high proportion of IFL loss in Russia (14%). There was also a large amount of IFL loss embodied in other secondary sectors and tertiary sectors, especially in mainland China (36%) and developed countries (e.g., the USA, Canada, Japan and Germany).

IFL loss embodied in international trade

Fig. 2A explores the linkages between producers of primary IFL-risk products and final consumers of final products. IFL loss associated with distant final consumption comprised 37% of global total anthropogenic IFL loss. Generally, displaced IFL loss was linked to the exports from IFL-rich regions (e.g., Russia, Canada, Southeast Asia, Oceania, Central Africa and Latin America) to developed (i.e., the EU and the USA) and emerging economies (i.e., mainland China). Meanwhile, source regions of mainland China's imports were more diversified than those of the EU and the USA.

Specifically, exports from Brazil and Rest of Latin America to the EU, mainland China and the USA were related to 103 kha, 85 kha and 81 kha of IFL loss respectively. The relatively small impact of mainland China on IFLs in Rest of Latin America is because pasture expansion comprised over 80% of the total agriculture-related IFL loss in tropical Latin America, while according to the Food and Agriculture Organization (FAO) FAOSTAT production and trade data [28], mainland China mainly imported cattle-related products from countries with little IFL loss, such as Argentina and Uruguay. For Russia and Africa, the major importers of IFL-risk commodities were the EU and mainland China, but the EU relied more on Russia (138 kha) and mainland China imported more from Africa (137 kha). For Canada, the USA was the leading export market, responsible for 139 kha of IFL loss, 100 kha more than that exported to mainland China. IFL-risk products originating from Oceania and Southeast Asia were predominantly sold to mainland China, linked to 146 kha and 73 kha of IFL loss, respectively.

Considering the heterogeneities of IFLs across different climate zones in terms of their potential to sequester carbon, conserve biodiversity and deliver other ecosystem services, Fig. 2B further classifies IFL loss into different biomes based on the spatial dataset “Terrestrial Ecoregions of the World” provided by the World Wildlife Fund [29], and investigates their connection with final consumers. Seventy percent of the global anthropogenic IFL area reduction took place in tropical and subtropical biomes (basically in Latin America, Central Africa, Southeast Asia and Oceania), while boreal (mostly in Russia and Canada), temperate (mostly in Canada) and Mediterranean (mostly in Australia) biomes accounted for 22%, 5% and 2%, respectively. For final consumers, the structure of source biomes varied between countries/regions. Of all the IFL loss embodied in mainland China’s final consumption, over 2/3 was sourced from tropical and subtropical biomes and 15%, 8% and 7% came from boreal, temperate and Mediterranean biomes, respectively. The EU and the USA imported less share of IFL-risk products from tropical and subtropical biomes (52% and 42%, respectively), whereas boreal regions contributed approximately 40% for each of the two. For major final consumers who were also dominant primary producers, final demand was mainly satisfied at the expense of local IFL loss. Other regions’ final consumption generally threatened more tropical and subtropical IFLs than IFLs in other biomes. Overall, 1/3 of tropical and subtropical IFL loss was driven by export production, but the ratio was over 40% for boreal and temperate IFL loss.

Displaced IFL loss by proximate causes

When tracing embodied IFL loss back to its proximate causes, it can be found that, different countries and regions influenced IFLs through distinct pathways (Fig. 3). Logging-driven IFL loss made up the largest share of total displaced IFL loss (1.04 Mha, 51%), followed by mining and energy extraction (0.53 Mha, 26%) and agriculture (0.46 Mha, 22%). Logging-driven IFL loss was primarily embodied in the exports from Canada, Russia, Southeast Asia, Oceania and Sub-Saharan Africa to East Asia (especially mainland China), the USA and the EU. IFL loss caused by other economic activities was associated with similar importers but can be traced back to different source regions. 83% of displaced agriculture-related IFL loss originated from Latin America, with Brazil alone contributing 42%, while displaced IFL loss from mining and energy extraction primarily came from Russia (43%), Australia (22%) and Latin America (28%). Generally, 62% of mining/energy-induced IFL loss was associated with export production, but the shares for logging and agriculture only reached 40% and 23% respectively. In regard to final consumption, logging-related IFL loss was linked to consumers worldwide, led by China as an individual economy. Almost 70% of the agriculture-related IFL area reduction was associated with the final consumption of Latin America, while Russia and the EU were responsible for the largest share of IFL loss from mining and energy extraction (23% and 17% respectively).

Fig. 4 further illustrates the displacement of IFL loss by proximate causes for major primary producers and final consumers. For Latin America, Central Africa, Canada, Russia and Indonesia, approximately 23% – 49% of local IFL loss was related to export, but the ratio reached 78% and 65% for Australia and Rest of Oceania & Southeast Asia. There are obvious differences in the share exported by different proximate causes for different source regions. In Latin America, IFL loss from agriculture was exported to a much larger degree than that from mining/energy and logging, but local demand still represented 76% and 83% of the total agriculture-induced IFL loss in Brazil and Rest of Latin America, respectively, which is consistent with FAO production and trade data. For Central Africa, Canada, Indonesia and Rest of Oceania & Southeast Asia, most of the IFL loss embodied in export was sourced from logging. The contribution of external demand to IFL loss in Central Africa was lower than potentially expected. This lower damage is because even though forestry companies in the DR Congo are typically foreign-owned, a large portion of their output is aimed for domestic markets [30]; meanwhile, for Gabon and Republic of Congo where natural forests are publicly owned, FAO Yearbook of Forest Products also confirms that domestic demand were responsible for a substantial share of wood-based products [31].

Mining and energy extraction was the dominant proximate driver of IFL loss embodied in exports from Russia and Australia, even though logging-related IFL loss was more pervasive in Russia. The import structures by proximate causes for China and the USA were similar: over 60% of the IFL loss embodied in their imports came from logging, followed by mining/energy (contributing 19% and 25%, respectively). For the EU, mining/energy (41%) prevailed over the other two proximate causes.

Discussion

We have comprehensively investigated IFL loss across global supply chains and revealed distinctly different patterns that complement studies solely focusing on deforestation. There are some uncertainties in our estimation because multiple data sources and certain attribution models are adopted to allocate IFL loss to different economic sectors and to different years due to a lack of detailed data. Sectoral and regional aggregations in the multi-regional input-output model also preclude us from identifying supply chain agents at a higher resolution and may lead to the misestimation of the influence of international trade. However, both qualitative insights from the literature and quantitative insights from sensitivity analyses support the reliability of our findings. Please see the Uncertainties and Limitations section for more details.

Our results uncovered the notable contribution of non-agricultural products in shaping IFL loss displacement: logging-induced IFL loss comprised the largest share; More strikingly, although the IFL loss from agriculture was more than double that from mining and energy extraction, the displaced IFL loss that was directly caused by mining and energy extraction was larger in magnitude. These results highlight the need to assess the broader impacts of global supply chains, not only on agriculture-dominated deforestation, but also on the prevalent forest fragmentation and degradation from various economic activities. However, selective logging is still promoted as a sustainable management practice by many tropical countries and accepted by some influential international programs (e.g., Reducing Emissions from Deforestation and Forest Degradation (REDD) program and Forest Stewardship Council (FSC) certification program) [32], even though it is becoming an important agent of fragmentation and degradation of the world's most precious tropical forests [18,33]. Current pledges made by companies also pertain to deforestation from traditional forest and agricultural commodities, such as timber, pulp, soy, beef and palm [34], neglecting the threats from mining and energy extraction, which will be more pivotal in the ongoing global transition towards a green energy system [35]. Moreover, a large share of IFL loss was embodied in downstream sectors, such as construction, service and manufacturing of highly processed products. Trade analyses solely focusing on the primary products directly responsible for forest disturbance can greatly underestimate IFL loss displacement and consequently mislead demand-side policies. This reflects the relevance of land use analyses from a consumption-based perspective.

Given the pervasive displacement of IFL loss, mutual efforts of producer and consumer countries are required to preserve remaining IFLs. There have already been many voluntary initiatives against deforestation. Examples on the supply side include corporate pledges (e.g., zero-deforestation commitments) and collective aspirations (e.g., New York Declaration on Forests). Targeting IFL loss other than deforestation can complement existing efforts in these aspects. For instance, among all the companies with a zero-deforestation commitment, 44% adopt a net-zero target, which allows afforestation to compensate deforestation of the same size [34]. This may lead to the situation where primary forests rich in biodiversity and carbon stocks are replaced by managed forests. Such conversion could be mitigated if a zero-IFL-loss target is integrated into the commitment, as the concept distinguishes managed and natural intact forests. There are also various consumer campaigns and supply chain initiatives, such as the Roundtable for Sustainable Palm Oil, the Roundtable for Responsible Soy and the Programme for the Endorsement of Forest Certification. FSC has introduced rules for IFL protection since 2017, but it allows 20% of IFLs to be exploited [36]. Apart from the problem of leniency, this type of approach will also be hard to duplicate for many other IFL-risk commodities, because their links to IFL loss are more indirect for individual final consumers compared to traditional agricultural and forest products. For example, it is widely concerned that beef production drives deforestation in the Amazon, but it is hard for consumers to realize that the production of highly processed equipment may involve timber and metals produced at the expense of IFL loss and that services provided by tertiary sectors may be supported by electricity generated from oil and gas associated with IFL loss. Voluntary measures may also suffer from other problems such as low/selective adoption, insufficient market uptake, corruption and patrimonialism [34].

The much more dispersed nature of IFL loss drivers and the weaknesses of private interventions call for stronger engagements of both national governments and international institutions. For instance, producer governments can introduce mandatory due diligence for corporations and transparency regulations for financial institutions [37]. It is also crucial to implement more stringent land use policies, e.g., through land-use zoning policies, such as protected areas and biodiversity corridors. Variations in IFL loss drivers across countries and sectors require tailored forest conservation strategies. For Latin America, combating agricultural encroachment is the primary challenge. For Russia, Canada, Southeast Asia, Oceania and Central Africa, policies should target industrial logging, with mining/energy extraction as another focus for Russia and Canada and agricultural expansion for other regions. Meanwhile, consumer countries and international institutions can support producer countries (especially where forest conservation institutions are lacking or severely underfunded) in specific initiatives or general capacity building, such as improving governance, ensuring land rights, enhancing productivity and establishing a monitoring and verification system that can improve the traceability and transparency of supply chains. International demand may also spark illegal forest development: approximately 50% and 25% of illegal timber in international trade came from Indonesia and Brazil in 2013, respectively [38]. Consumer countries can therefore enforce regulations to combat illegal logging and deforestation (e.g., EU Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan), for example, by validating the source of imported products. Of course, there are many other policy options that have not been listed here, such as “nudging” and behavioral designs, carbon tax, ecological payments and trade tariffs. However, considering the complex trade-offs between potential outcomes and policy feasibility, all of the proposed options should be explored and adopted with caution [37].

In the future, forests are facing fiercer threats from multiple sectors, as more resources are needed to feed a growing population and to support quality life for all. In this context, advancing the knowledge of IFL loss has become increasingly crucial. However, neither the proximate IFL loss cause nor its connection with complex socio-economic dynamics has been sufficiently studied. The problem, to a large extent, is due to a lack of data suitable for comprehensive and in-depth interdisciplinary analyses. Therefore, researchers from land-use, geographic and social sciences should strengthen cooperation, to develop a robust globally consistent dataset that has higher spatial, temporal and commodity resolution. Beyond risks from different sectors, there are also trade-offs between different environmental and socio-economic targets. For example, commercial logging and subsistence agriculture in forest areas can help eradicate poverty and underpin local livelihood [39]. Smallholder subsistence agriculture is an important source of employment and livelihoods for women in rural places (supporting more than two-thirds of working women in Africa) [40]. At least 36% of the world’s IFLs are within indigenous and tribal territories [41]. Unbalanced conservation policies may impede social stability and the achievement of United Nations Sustainable Development Goals (SDG), such as SDG No.1 (No poverty), SDG No.2 (Zero hunger) and SDG No.5 (Gender equality). As a result, it is critical that the synergies and trade-offs between sustainable development goals in different domains are fully understood and considered in policy-making. The coordination efforts require multidisciplinary planning as well as voices from different interest groups across different scales.

Experimental Procedures

Resource Availability

Lead contact: Further information and requests should be directed to and will be fulfilled by the lead contact, Bin Chen (chen_bin@fudan.edu.cn).

Materials availability: This study did not generate new unique materials.

Data and code availability: All the data sources and mathematic models used in this paper are elaborated in the Experimental Procedures and summarized here, including loss of intact forest landscapes [1], drivers of global forest loss [33], global mining areas [42], FAO land use [43], principal mineral areas, producing mines, and oil and gas fields in Canada [44], locations of global hydropower plants [45], the European Space Agency (ESA) CCI global land cover maps [46] and GTAP multi-regional input-output table [27]. Data on the loss of intact forest landscapes associated with domestic consumption, import and export are available in the Supplemental Information. Any additional information required to reanalyze the data reported in this paper will be shared by the lead contact upon request.

Attribution of IFL loss to economic sectors

Data on IFL loss were taken from Potapov et al.[1], which recorded IFL area reduction per country in 2000-2013, based on the global archive of Landsat satellite imagery supplemented with national transportation maps, high-resolution maps from Google Earth and other forest cover change products. They then applied a stratified sampling approach to identify the proximate causes of IFL loss for 9 aggregated regions, which were further examined with all accessible remote sensing data. The proximate drivers were divided into five categories, including wildfires, industrial logging, agricultural expansion (including pasture expansion), mining/oil and gas/hydropower as well as transportation for other aims. IFL loss from wildfires was not included in our calculation.

We first need to identify IFL loss by proximate drivers per country. By integrating the geographic boundaries of the 9 aggregated regions and the data on IFL loss, we can obtain driver-specific IFL loss for Canada, Russia and Australia. For other countries, we took the following procedures: (1) the IFL loss map was overlapped with a map of agriculture-driven forest cover loss [33], in order to estimate each country's relative contribution to regional total agriculture-induced IFL loss. Then, the IFL loss from agriculture per country was calculated by multiplying the regional total by the corresponding shares. (2) IFL loss from mining and energy extraction per country was calculated following the same principle in (1). To assess each country's share of regional total mining/energy-related IFL loss, the IFL loss map was overlapped with a map of global mining areas [42]. We applied a 70 km buffer around mining sites, given that forest disturbance may extend up to 70 km from mining leases [47]. (3) Regarding IFL loss from other transportation, which represented only 2% of global total anthropogenic IFL loss, we assumed it was proportional to national overall IFL loss. (4) Finally, logging-related IFL loss per country was obtained by subtracting the IFL loss caused by other proximate drivers from the national total. This is because a large proportion of logging-related IFL loss was due to degradation and fragmentation from selective logging, in which case the disturbed landscapes remained forest landscapes in land cover maps and were more difficult to distinguish from forest wildlands compared to agriculture and mining areas.

We then allocated IFL loss to specific economic sectors in the GTAP input-output table (IOT) as a base for multi-regional input-output analysis, in order to track IFL loss across global supply chains. IFL loss from logging and other transportation can be directly attributed to the forestry and land/pipeline transport sectors respectively, but IFL loss due to other causes needs to be disaggregated to fit IOT sectoral resolution. Following Pendrill et al. [14,16], areas occupied for different agricultural uses were attributed in relative proportion to the expansion of each agricultural sector's direct land use, based on the land use data from FAO [43]. For example, if wheat represented x% of the total agriculture expansion, x% of the agriculture-related IFL loss would be assigned to the wheat production sector. Potapov et al. noted that pasture expansion contributed 81.5% of the overall agriculture-related IFL loss in tropical South America, so 81.5% of IFL loss was attributed to cattle farming before we estimated the contribution of other agricultural sectors. Most of mining/energy-related IFL loss took place in tropical South America, Australia, Canada and Russia. For Latin America and Australia, mining (mostly gold exploration) was the primary cause, therefore, IFL loss was attributed to the mining sector [1]. For Canada, we separated the contributions of mining, oil and gas extraction and hydropower production by integrating the IFL loss map, the abovementioned global mining map [42], the map of oil and gas field provided by Natural Resources Canada [44] and the geographic coordinates of global hydropower plants provided by Global Power Plant Database [45]. Sonter et al. found that off-lease impacts of mining within surrounding 70 km buffers were due to secondary forest clearing, urban expansion to support the workforce and other mining-stimulated economic activities [47]. Such a cascade influence should also exist during oil, gas and hydropower production, so we consistently assume a 70 km impact buffer for all these sites. In Russia, oil and gas extraction was the disturbing factor [1], where IFL reduction was equally assigned to the oil and gas sectors due to a lack of data.

Amortization of IFL loss

Attributing IFL loss to drivers implies not only specifying which activities (i.e., economic sector or production of a given commodity) cause the loss, but also accounting for the temporal dimension of the link between IFL loss and economic activities. That is, while IFL loss is a one-off event, the follow-up production typically persists over long timeframes. For example, an oil palm or acacia plantation or a bauxite mine established within an intact forest area will generate palm oil, pulp and aluminum products over many years, not seldom with a time-lag between IFL loss and production (oil palms only start generating fruit after three years, and acacia pulp plantations typically have a rotation period of seven years) [48,49]. For this reason, one cannot simply assign IFL loss to economic activities in the same year, but land-use changes (as well as associated environmental impacts) are typically amortized, or spread out, over several years of production. This means that with an amortization time of T years, the IFL loss embodied in economic activities in a given year should be the total IFL loss in the previous T years divided by T.

The choice of amortization period is ultimately normative and there is no agreed-upon choice. In life cycle assessment, an amortization period of 20 years is typically advocated [50], but different amortization periods are used in the literature on deforestation embodied in trade (typically in the range of 1-10 years) [48,49]. Here we adopted an amortization period of 13 years for pragmatic reasons: the IFL data are aggregated over the period 2000-2013 and cannot easily be disaggregated to an annual time-series (i.e., there are no obvious proxies that can be used to infer annual IFL loss in the period). Unless there are large fluctuations in IFL loss in a given country or region, the choice of a thirteen-year amortization period should not affect our estimation of the roles of different countries in global supply chains [48].

It is common that forestry land is later converted to agricultural land [51], and part of the IFL loss should be allocated to the follow-up activities. According to Potapov et al., in Africa and Southeast Asia, logging-induced IFL loss was caused by selective logging, which means that the landscape remained forest land cover and would not be easily occupied by agriculture and other industries. Monoculture plantations were found to follow selective logging but only contributed 0.2% of the global total IFL area reduction. Considering that it is also unknown since when logging sites were converted to plantations, IFL loss was not attributed to follow-up production. In Latin America, there is no specific description about which kind of logging method was used, but it is stated that new cropland mainly occurred in pastures previously converted from forests, which is also confirmed by ref. [51]. To estimate the successive land use change, we overlapped the 300-m-resolution ESA-CCI global land cover maps [46] with the IFL loss map. The class “Grassland” in ESA CCI maps was used to represent pastures (existing time-series high-resolution global land cover maps do not distinguish natural grassland and pastures) and the class “Agriculture” (including grids of cropland and grids of mosaic cropland/natural vegetation) was used to represent cropland, in order to estimate the maximum probability of pasture-cropland conversion on an annual basis. No grids detecting pasture-cropland conversion in the period concerned were found to overlap with IFL loss patches. In North America and Eurasia, clear-cutting was the main culprit of logging-related IFL loss. Meanwhile, mining/energy-related IFL loss was associated with oil and gas production in Eurasia and primarily associated with hydropower production in North America, and we inferred that these oil, gas and hydro fields would not be used for other aims during such a short period. We followed the same method mentioned above to estimate the maximum probability of agricultural encroachment into logging and mining areas. Little grids detecting new agricultural land since 2000 were within lost IFLs, even though we have overestimated the potential distribution of agricultural land.

Embodiment accounting

The embodiment accounting is carried out based on multi-regional input-output (MRIO) analysis, which has been adopted to account for a variety of ecological elements (e.g., energy [52,53] and carbon emissions [54,55]). Within the framework of the multi-regional input-output model, the world economic system consists of *m* regions, each with *n* sectors. Intermediate trade denotes transactions between industrial sectors while final trade depicts transactions between sectors and final consumers. Land use responsible for IFL loss is embodied in IFL-risk products, and therefore can be traced as product embodiments from countries witnessing IFL loss to final consumers of related products. Sectoral input of IFL-risk land use comprises IFL loss induced by the sector directly (marked as *l*), and that embodied in imported intermediate products (*z*), while sectoral output consists of IFL loss embodied in all the outputted products in both intermediate and final trade (*f*). As elaborated by the law of conservation of resource use, total sectoral input equals sectoral output [56], which generates the following equation for sector *i* in region *r*:

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

where z_{ji}^{sr} stands for intermediate input to sector i in region r from sector j in region s. f_{ic}^{rs} represents the final output from sector *i* in region *r* to region *s* for final consumption. ε_i^r denotes the IFL loss associated with the unit output of sector i in region *r*.

Equation (1) can be transformed into matrix form:

$$\boldsymbol{L}+\boldsymbol{\varepsilon Z}=\boldsymbol{\varepsilon X} \tag{2}$$

where $\boldsymbol{\varepsilon}=(\varepsilon_i^r)_{1\times mn}$, $\boldsymbol{L}=(l_i^r)_{1\times mn}$, $\boldsymbol{Z}=(z_{ij}^{rs})_{mn\times mn}$, $\boldsymbol{X}=\mathrm{diag}(x_i^r)_{mn\times mn}$ ($x_i^r=\sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs}+\sum_{s=1}^{m} f_{ic}^{rs}$, denotes the sectoral total output). Therefore, ε can be obtained as:

$$\boldsymbol{\varepsilon}=\boldsymbol{L}(\boldsymbol{X}-\boldsymbol{Z})^{-1}=\boldsymbol{L}\boldsymbol{X}^{-1}(\boldsymbol{I}-\boldsymbol{A})^{-1} \tag{3}$$

where $\boldsymbol{I}$ is the identity matrix with dimensions $mn \times mn$ and $\boldsymbol{A}=\boldsymbol{Z}\boldsymbol{X}^{-1}$.

IFL loss embodied in the sectoral input/output can be obtained by multiplying their volume by the corresponding intensity ε_i^r. For example, for region *r*, the IFL loss embodied in its final consumption (LC^r) can be calculated as:

$$LC^r=\sum_{s=1}^{m}\sum_{j=1}^{n}\varepsilon_j^s f_{jc}^{sr} \tag{4}$$

Multi-regional input-output tables (IOTs) were collected from the GTAP database [27], given that GTAP covers 141 countries, which enables investigation of detailed information for major producer and consumer countries and regions, and 65 sectors, which allows us to distinguish the impacts of different economic sectors.

Uncertainties and Limitations

First, there are some uncertainties in the attribution of IFL loss. The criteria and method to identify IFL loss and its primary causes are more complicated than those to identify deforestation. The massive remotely sensed data as well as data processing required make it even more challenging to replicate the work of Potapov et al., not to mention allocate IFL loss to economic sectors at higher sectoral resolution, for lack of high-resolution spatial information on land use. Therefore, we relied on multiple data sources and certain attribution model to estimate IFL loss by proximate drivers and by specific sectors at a national scale. The model we applied and the inconsistencies between different data sources (e.g., spatial resolution and identification approach) may cause some deviations. Therefore, we provided a sensitivity analysis (abbreviated below as SA for convenience of presentation) by assuming that the IFL loss caused by each proximate driver fluctuates around the baseline (values obtained based on our method) by 10%, 20% and 30% of each country's total IFL loss respectively (SA-driver), and assuming that the IFL loss allocated to each sector fluctuates around the baseline by 10%, 20% and 30% of each country's IFL loss from the corresponding driver respectively (SA-sector), on the premise that all the results are consistent with the findings of Potapov et al (e.g., total IFL loss per country and driver-specific IFL loss per region). As mentioned above, we can obtain driver-specific IFL loss for Canada, Russia and Australia from existing data, so the SA-driver analyses were only performed for Latin America, Asia-Pacific (excluding Australia) and Africa (see Supplemental Information). The results show that different allocation schemes mainly affect IFL loss associated with the final consumption of producer countries, mainland China and the USA, because IFL loss in producing countries would be allocated to sectors that were more/less export-oriented in SA, while mainland China and the USA were dominant export markets. Such influence is very limited in the SA for the Asia-Pacific, Africa, Russia and Canada while it is more evident in the SA for Latin America, but generally, dominant final consumers still hold their leading positions.

Second, the MRIO model has some uncertainties. The input and output of individual companies are aggregated to a sectoral level in input-output tables, and it is also unknown which companies were responsible for the IFL loss, precluding us from identifying whether IFL-risk commodities were sold to domestic or foreign markets specifically. However, local IFL loss is a combined result of both internal and external demand. For example, if there is no timber consumption domestically, then foreign demand can be satisfied by timber production in existing logging sites, avoiding further expansion of forestry land use into IFLs. In this sense, it is reasonable to use aggregate sector-level trade data rather than company-level trade data to reveal the potential and indirect driving effects of distant consumers. Meanwhile, the DR Congo is part of the aggregated region South Central Africa and Gabon and Congo are part of the aggregated region Rest of Central Africa. Production and trade data on roundwood, sawnwood, wood-based panels and wood charcoal show that, the share of export in total production for South Central Africa and for the DR Congo were very similar, while the share for Rest of Central Africa was slightly lower than the share for Congo and Gabon [31]. Therefore, the IFL loss associated with exports from Rest of Central Africa might be underestimated. The abovementioned uncertainties from sector and spatial aggregation have been well addressed by previous studies [57]. Physical accounting is another frequently applied tool, which utilizes physical bilateral trade data on primary and processed commodities and therefore can trace resource use and environmental impacts at a more detailed commodity level [58]. However, this advantage is diminished here, because detailed information on responsible companies/commodities is lacking. In addition, physical accounting has limitations in capturing flows of highly processed products (to which a large share of IFL loss was linked) and determining actual end users.

Third, there are also uncertainties arising from the amortization of IFL loss. The length of the amortization period may affect our results, but we were not able to perform sensitivity analyses because there are no appropriate references to disaggregate IFL loss to an annual time-series and the recent data on IFL loss in 2014-2020 do not distinguish specific proximate drivers [7]. Meanwhile, considering trade-offs between time, country and sector resolutions, we adopted the 2014 GTAP IOT for MRIO analysis (there is no IOT for 2013), assuming that the difference between the IFL loss in 2000-2013 amortized over 13 years and the IFL loss in 2000-2014 amortized over 14 years can be ignored. According to Global Forest Watch [59], loss of global primary forests (here $\geq 20\%$ canopy density) did not accelerate until 2016 and there was little difference between annual average primary forest loss in 2000-2013 and in 2000-2014. Meanwhile, we overlaid the map of wildfire-driven forest cover loss [33] with the maps of IFLs in 2000, 2013 and 2016, respectively, to estimate the annual average anthropogenic IFL loss in 2000-2013 and in 2000-2016 (we applied the same method for 2000-2013 instead of using existing data for consistency). The difference between the two values is less than 0.05 Mha for most countries, which also supports our assumption. Detailed analyses of the influence of amortization periods can be found in ref. [48].

Given these, an uncertainty analysis of the overall results has been performed to reveal the uncertainties by adopting a stochastic modelling[60,61]. The basic items $\boldsymbol{L}$, $\boldsymbol{Z}$ and $\boldsymbol{F}$ were perturbed 10000 times by introducing the standard deviation using Monte Carlo simulation, based on which the perturbed demand-driven IFL loss can be obtained. More technical details and source codes can be found in our previous work [62,63]. The relative standard deviation of the IFL inventory and GTAP MRIO used in this work could be derived from Potapov et al. [1] and Hertwich et al.[64], respectively. The uncertainties of the IFL loss embodied in final consumption varied from region to region, from [-5.6%, +6.6%] for China to [-10.1%, +10.5%] for Brazil at the 95% level of confidence (detailed results are presented in Table S4).

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Declaration of Competing interests

The authors declare no competing interests.

Figure captions

Figure 1 Loss of intact forest landscapes (IFLs) associated with final consumption. Panels (A-C) break down IFL loss (A) by sector for major final consumers, (B) by sector for 6 region groups and (C) by percentage attribution to countries and regions. Panel (D) shows the links between proximate causes of IFL loss (left) and final consumption sectors (right). A full list of countries and regions is provided in Supplemental Information.

Figure 2 Loss of intact forest landscapes (IFLs) associated with international trade. Panel (A) shows the displacement of IFL loss between the primary producers and final consumers. Only flows greater than 30 kha are marked. Panel (B) depicts source-to-sink budget of IFL loss. The left and middle columns represent IFL loss by regions and climate zones where it took place and the right column represents IFL loss embodied in final consumption by final consumers. "Rest of" regions on the left and right sides respectively refer to aggregations of all the countries not listed in corresponding columns.

Figure 3 Displaced loss of intact forest landscapes (IFLs) traced back to proximate causes.

Panels (A-B) further attribute displaced IFL loss to direct exploiters and final consumers, respectively. Panel (C) shows the share of displaced IFL loss in total loss caused by a specific economic activity. Panel (D) disaggregates IFL loss associated with final consumption by proximate causes and final consumers.

Figure 4 Regional contribution to production- and consumption-related intact forest landscape (IFL) loss.

Panel (A) reveals the influence of local consumption and export production on local IFL loss for dominant producer regions and Panel (B) compares the share of local consumption and import in total consumption-related IFL loss for dominant consumer regions.