Global Drivers of Russian Timber Harvest

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Supporting information is available on the *JIE* Web site

Summary

Russian forest resources are important for global carbon cycling. In contrast to traditional analyses that focus on the harvest and direct use of Russian timber resources (a.k.a. production-based accounting), this study investigates how the consumption of nations drives Russian timber harvest (a.k.a. consumption-based accounting or the Russian timber footprint). China is the biggest direct importer and final consumer of Russian timber. The United States, Japan, and major European countries directly import relatively small amounts of Russian timber, but serve to drive large amounts of Russian timber harvest through their final consumption. Through structural path analysis, individual supply chain paths are delineated to show linkages between Russian timber harvest and the final consumption of nations. Findings of this study inform consumption-side measures for Russian forest conservation, for example, taking shared responsibility and improving the production efficiency of key sectors in consuming nations.

Introduction

Harvesting and conversion of forests contribute around 20% of global greenhouse gas (GHG) emissions each year (Denman et al. 2007). Russia represents approximately 22% of forest cover and over 50% of coniferous forests in the world (Potapov et al. 2008). Russia's forest quality (e.g., natural productivity and forest age) is experiencing a continuous decline (FAO 2015; Newell and Simeone 2014) to which timber harvest is a major disturbance (Cushman and Wallin 2000; Achard et al. 2006). Therefore, Russian timber harvest is a significant contributor to global GHG emissions. To help reduce Russian timber harvest and, consequentially, mitigate global GHG emissions, it is crucial to identify consumption drivers for Russian timber harvest and investigate how these consumption drivers historically evolve.

Perestroika (1986–1991) abolished export controls and transformed the Russian timber sector into an export-oriented industry (Newell 2004, 2006; Lankin 2005; Newell and Simeone 2014), as a result of which Russia becomes a major roundwood exporter in the world (Robbins and Perez-Garcia 2012; Newell and Simeone 2014). Given the importance of international trade in driving forestry-related issues, such as biomass uses (Wiedmann et al. 2015), deforestation (Jonas et al. 2013), and land-use changes (Weinzettel et al. 2013), analyzing foreign consumption drivers for Russian timber harvest can help policy decisions from the consumption side.

From a traditional production-based perspective, perhaps major Russian timber importers, such as China—the largest importer of Russian roundwood (Newell and Simeone 2014; Robbins and Perez-Garcia 2012)—should take the primary responsibility of reducing Russian timber consumption to mitigate environmental impacts associated with Russian timber harvest. However, major Russian timber importers (e.g., China and South Korea [Newell and Simeone 2014]) are usually manufacturing nodes within global supply chains, not the end-use drivers (i.e., final consumption drivers) for Russian timber harvest. For example, the United States does not import Russian roundwood (FAO 2015). However, U.S. consumption drives Russian roundwood harvest through global supply chains (e.g., U.S. households purchase books from Canada; those

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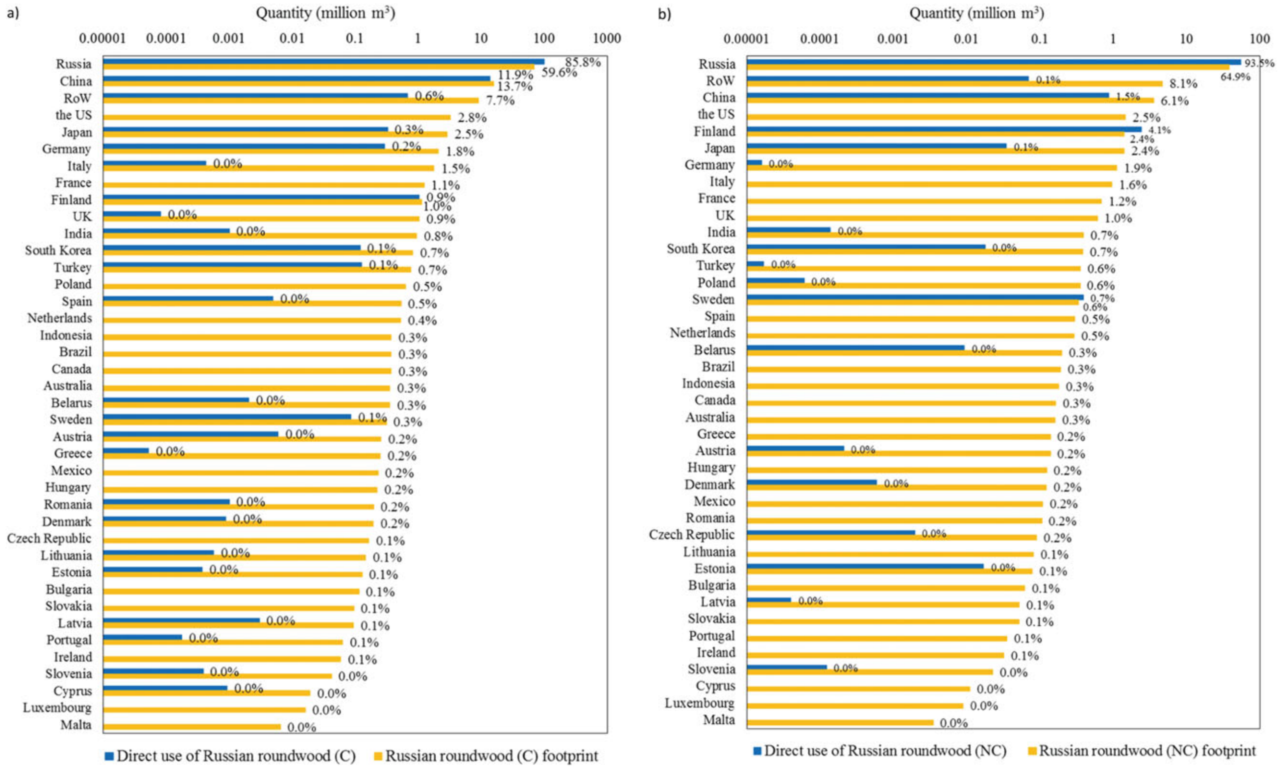

Figure 1 Direct use of Russian roundwood and Russian roundwood footprint for nations in 2011: (a) coniferous (C) and (b) nonconiferous (NC). The horizontal axis is in logarithmic format. Detailed data are listed in table S1-1 in the supporting information on the Web.

books are made of paper from China; and China produces the paper using Russian roundwood). Existing studies overlooked final consumption drivers for Russian timber harvest, which can help policy decisions from the consumption side to reduce Russian timber harvest and, consequentially, contribute to global GHG mitigation.

The purpose of this article is to identify final consumption drivers for Russian timber harvest. More specifically, research questions of this study are: (1) Which nations and sectors are the most important final consumption drivers for Russian timber harvest?; (2) Which supply chain paths are the most important paths linking Russian timber harvest with final consumers?; and (3) How do final consumption drivers for Russian timber harvest historically evolve?

This study answers these questions using a consumption-based method that evaluates both direct and indirect resource uses or environmental emissions caused by final consumers (Davis and Caldeira 2010; Peters 2008; Liang et al. 2015). Consumption-based environmental pressures are also known as environmental footprints (Wiedmann 2009). This study uses a mixed-unit multiregional input-output (MU-MRIO) model to analyze time-series Russian timber footprints of nations. Structural path analysis (SPA) is used to analyze critical supply-chain paths linking Russian timber harvest with final consumers.

Methods and Data

Mixed-Unit Multiregional Input-Output Model

A multiregional input-output (MRIO) model characterizes intersectoral interdependence within and among regions. Suppose there are m regions and n sectors in each region. Row balances of an MRIO model can be described by equation (1):

$$\boldsymbol{x} = (\mathbf{I} - \mathbf{A})^{-1}\, \boldsymbol{y} \qquad (1)$$

where $\boldsymbol{x}$ is an $(s = n \times m) \times 1$ vector indicating total output of each sector in each region; $\mathbf{I}$ is a $s \times s$ identity matrix; $\mathbf{A}$ is a $s \times s$ matrix indicating technical coefficients (Miller and Blair 2009); $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the *Leontief inverse* matrix (Miller and Blair 2009); and $\boldsymbol{y}$ is a $s \times 1$ vector representing final demand of each sector in each region. In particular, the matrix $\mathbf{A} = \mathbf{Z}\hat{\boldsymbol{x}}^{-1}$, where $\mathbf{Z}$ is a $s \times s$ matrix indicating exchanged goods and services among region-sectors.

We can construct an MU-MRIO model by separating investigated subsectors out of aggregated sectors. Rows indicating those separated subsectors are expressed in physical units, whereas rows indicating other sectors are expressed in monetary units. Mixed-unit input-output models have been applied to study metal flows (Hawkins et al. 2007), wind power (Wiedmann et al. 2011), and biofuels (Liang et al. 2012, 2013).

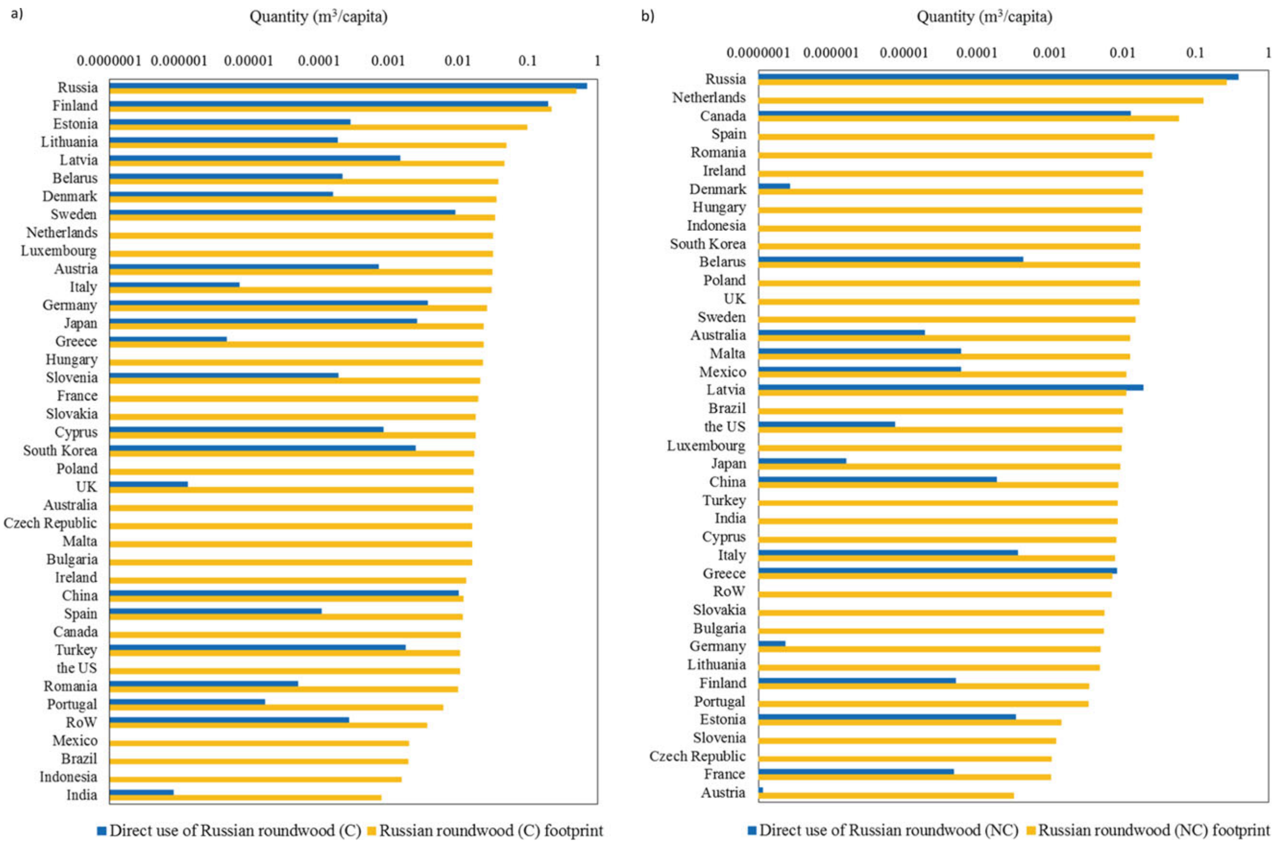

Figure 2 Per capita direct use of Russian roundwood and per capita Russian roundwood footprint for nations in 2011: (a) coniferous (C) and (b) nonconiferous (NC). The horizontal axis is in logarithmic format. Detailed data are listed in supporting information table S1-2 on the Web.

Suppose the MU-MRIO model has k rows in physical units and s rows in monetary units. The technical matrix of the MU-MRIO model is expressed as shown by equation (2):

$$\mathbf{A}^* = \begin{pmatrix} \mathbf{P} & \mathbf{C}_\mathrm{D} \\ \mathbf{C}_\mathrm{U} & \mathbf{A}' \end{pmatrix} \tag{2}$$

where $\mathbf{P}$ describes physical transactions among k sectors for unitary total output of each sector (mass/mass); $\mathbf{C}_\mathrm{D}$ represents direct requirements for the k sectors by unitary output of s sectors (mass/\$); $\mathbf{C}_\mathrm{U}$ indicates direct requirements for s sectors by unitary output of k sectors (\$/mass); and $\mathbf{A}'$ shows monetary transactions among s sectors for unitary total output of each sector (\$/\$). In particular, $\mathbf{A}'$ is different from the term $\mathbf{A}$ in equation (1). Matrix $\mathbf{A}'$ is obtained based on the new $s \times s$ intermediate inputs matrix $\mathbf{Z}'$ in which the values of physical flows of k sectors have been subtracted from aggregated sectors.

We use equation (3) to calculate the footprint of regions for products from k sectors in physical units:

$$\mathbf{C}^* = (\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{Y}^* \tag{3}$$

where $\mathbf{Y}^*$ is a final demand matrix whose rows indicate region-sectors and columns represent final demand of each region on products from region-sectors; and matrix $\mathbf{C}^*$ indicates the footprint of each region for products from all region-sectors. Matrices $\mathbf{Y}^*$ and $\mathbf{C}^*$ are in mixed units, with k rows in physical units and s sectors in monetary units. The k rows in physical units in matrix $\mathbf{C}^*$ show footprint results for those investigated k sectors.

Structural Path Analysis

Whereas the total (direct and indirect) impact of final consumption on the output of particular sectors can be measured using an MU-MRIO model ($\boldsymbol{x}^* = (\mathbf{I}\text{-}\mathbf{A}^*)^{-1}\mathbf{y}^*$), it is also important to know what particular processes in the economy contribute the most to physical flows of k sectors. SPA is often used to identify and quantify the contribution of important supply-chain paths for particular impacts driven by particular consumption (Lenzen 2007; Skelton et al. 2011; Liang et al. 2014; Peters and Hertwich 2006). This is done by conducting the Taylor series expansion of the total requirement matrix $(\mathbf{I}\text{-}\mathbf{A}^*)^{-1}$, as shown by equation (4):

$$\begin{aligned}\boldsymbol{x}^* &= (\mathbf{I} - \mathbf{A}^*)^{-1}\,\mathbf{y}^* \\ &= \sum_{i,j=1}^{n}\left(1 + a_{ij}^* + \sum_{k=1}^{n} a_{ik}^* a_{kj}^* + \sum_{l=1}^{n}\sum_{k=1}^{n} a_{il}^* a_{lk}^* a_{kj}^* + \cdots\right) y_j^* \\ &= \sum_{i=1}^{n} y_i^* + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}^* y_i^* + \sum_{i=1}^{n}\sum_{k=1}^{n} a_{ik}^* \sum_{j=1}^{n} a_{kj}^* y_j^* + \cdots \end{aligned} \tag{4}$$

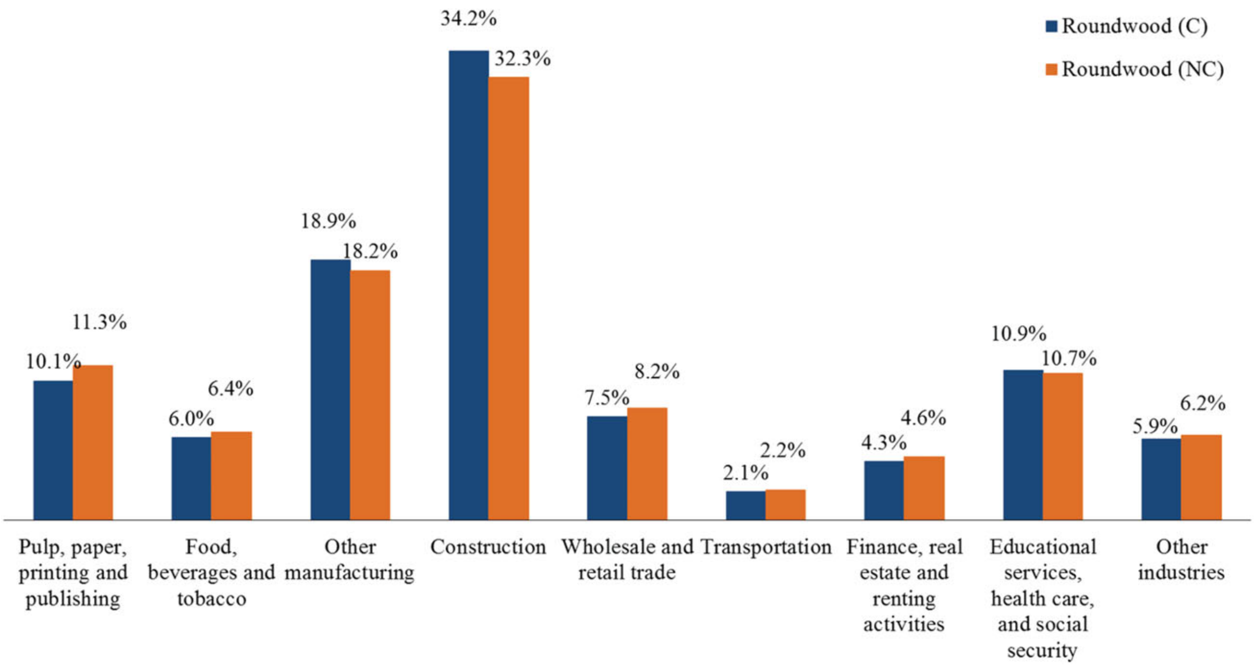

Figure 3 Russian roundwood footprint by sectors globally in 2011. Aggregation details from 35 sectors to nine sectors are shown in table S2-1, and detailed data are listed in table S1-3, in the supporting information on the Web.

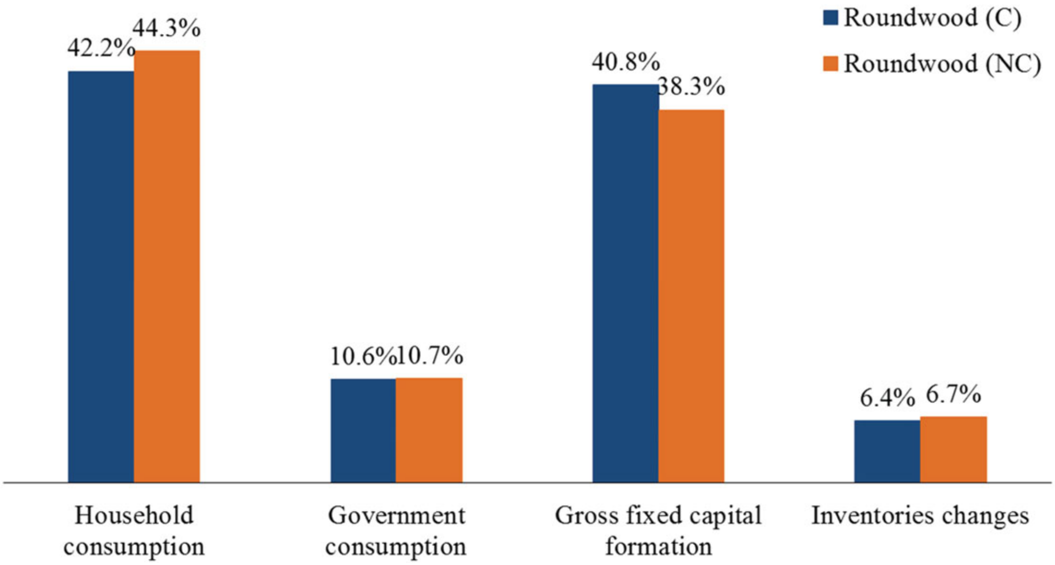

Figure 4 Russian roundwood footprint by final demand types globally in 2011. Aggregation details from five final demand types to four final demand types are shown in table S2-2, and detailed data are listed in table S1-4, in the supporting information on the Web.

where a_{ij}^* is the element of $\mathbf{A}^*$ and y_i^* is the element of $\boldsymbol{y}^*$. Each item in the right-hand side, for example, $a_{ik}^* a_{kj}^* y_j^*$, measures the impact of a two-step supply-chain path (sector $i \rightarrow k \rightarrow j$), happened in sector i, and caused by final demand of products from sector j. Vectors $\boldsymbol{y}^*$ and $\boldsymbol{x}^*$ indicate final demand and total output, respectively. They are in mixed units, with k rows in physical units and s sectors in monetary units.

Data Sources

In this study, we develop a MU-MRIO model for Russian timber harvest. The MRIO table is from the World Input-Output Database (WIOD; released in November 2013), which provides time-series MRIO tables for 40 nations and the Rest of the World (RoW), with 35 economic sectors per nation from 1995 to 2011 (Dietzenbacher et al. 2013; Timmer et al. 2015).

Table 1 Top 20 supply chain paths causing Russian roundwood (C) harvest in 2011

Rank	*Supply-chain path contribution (%)*	*Supply-chain paths*
1	11.14	Roundwood (C) → construction (RUS)
2	7.9	Roundwood (C) → pulp, paper, printing, and publishing (RUS)
3	6.79	Roundwood (C) → wood and products of wood and cork (RUS) → construction (RUS)
4	1.84	Roundwood (C) → wood and products of wood and cork (RUS)
5	1.78	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → food, beverages, and tobacco(RUS)
6	1.71	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → public administration and defense; compulsory social security (RUS)
7	1.66	Roundwood (C) → wood and products of wood and cork (RUS) → other manufacturing and recycling (RUS)
8	1.46	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → wholesale trade and commission trade, except of motor vehicles and motorcycles (RUS)
9	1.01	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → pulp, paper, printing, and publishing (RUS)
10	0.92	Roundwood (C) → wood and products of wood and cork (RUS) → wholesale trade and commission trade, except of motor vehicles and motorcycles (RUS)
11	0.83	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → retail trade, except of motor vehicles and motorcycles; repair of household goods (RUS)
12	0.59	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → education (RUS)
13	0.58	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → financial intermediation (RUS)
14	0.54	Roundwood (C) → pulp, paper, printing, and publishing (RUS) → health and social work (RUS)
15	0.52	Roundwood (C) → wood and products of wood and cork (RUS) → retail trade, except of motor vehicles and motorcycles; repair of household goods (RUS)
16	0.29	Roundwood (C) → wood and products of wood and cork (CHN) → other manufacturing and recycling (CHN)
17	0.28	Roundwood (C) → pulp, paper, printing and publishing (RUS) → other manufacturing and recycling (RUS)
18	0.25	Roundwood (C) → wood and products of wood and cork (CHN)
19	0.22	Roundwood (C) → pulp, paper, printing and publishing (RUS) → machinery, not elsewhere classified (nec) (RUS)
20	0.20	Roundwood (C) → pulp, paper, printing and publishing (RUS) → sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel (RUS)

Note: C = coniferous; RUS = Russia; CHN = China.

We use Russian timber data from the Food and Agriculture Organization (FAO) Forestry Trade Flows (FTF) database, which details export flows of two forest products (i.e., Russian coniferous roundwood [roundwood (C)] and nonconiferous roundwood [roundwood (NC)] for 120 nations (FAO 2015), to separate two subsectors (i.e., *Russian roundwood [C]* sector and *Russian roundwood [NC]* sector) from the Russian sector *agriculture, hunting, forestry, and fishing* of original WIOD tables. These two separated sectors are measured in physical units (cubic meters; m^3). It should be noted that timber is used in only certain sectors, instead of all 35 sectors of each country/region, which are: *mining and quarrying* (Conant and Fadem 2008; US-DoC 2005); *wood and products of wood and cork* (UNECE 2010); *pulp, paper, printing, and publishing* (Gerasimov and Karjalainen 2006); and *construction* (FAO 2012). Direct input coefficients of these two separated sectors are assumed to be the same as the Russian *agriculture, hunting, forestry, and fishing* sector. Given that the FTF data are only available after 1997, we construct a time-series MU-MRIO model from 1997 to 2011. The following steps show how the MU-MRIO model for Russian timber harvest is constructed.

Step 1: Obtain Russian Timber Trade Data

International trade data for Russian timber are from the FAO FTF database (FAO 2015). In particular, Mainland China and Taiwan are separately listed in the WIOD database, whereas the FAO FTF database aggregates them as one nation. We aggregate Mainland China and Taiwan in the WIOD database to be consistent with the FAO FTF database. The revised WIOD database includes 39 nations and the RoW. Moreover, international trade data for Russian timber in the FAO FTF database are in a 120-nation format. We aggregate those 120-nation data into a 40-region format to be consistent with the WIOD classification.

Table 2 Top 20 supply chain paths causing Russian roundwood (NC) harvest in 2011

Rank	*Supply-chain path contribution (%)*	*Supply-chain paths*
1	12.13	Roundwood (NC) → construction (RUS)
2	8.61	Roundwood (NC) → pulp, paper, printing, and publishing (RUS)
3	7.39	Roundwood (NC) → wood and products of wood and cork (RUS) → construction (RUS)
4	2.01	Roundwood (NC) → wood and products of wood and cork (RUS)
5	1.94	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → food, beverages, and tobacco (RUS)
6	1.87	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → public administration and defense; compulsory social security (RUS)
7	1.81	Roundwood (NC) → wood and products of wood and cork (RUS) → other manufacturing and recycling (RUS)
8	1.59	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → wholesale trade and commission trade, except of motor vehicles and motorcycles (RUS)
9	1.1	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → pulp, paper, printing, and publishing (RUS)
10	1.01	Roundwood (NC) → wood and products of wood and cork (RUS) → wholesale trade and commission trade, except of motor vehicles and motorcycles (RUS)
11	0.91	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → retail trade, except of motor vehicles and motorcycles; repair of household goods (RUS)
12	0.67	Roundwood (NC) → wood and products of wood and cork (FIN) → construction (FIN)
13	0.65	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → education (RUS)
14	0.63	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → financial intermediation (RUS)
15	0.59	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → health and social work (RUS)
16	0.57	Roundwood (NC) → wood and products of wood and cork (RUS) → retail trade, except of motor vehicles and motorcycles; repair of household goods (RUS)
17	0.31	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → other manufacturing and recycling (RUS)
18	0.26	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → renting of machinery and equipment and other business activities (RUS)
19	0.24	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → machinery, not elsewhere classified (nec) (RUS)
20	0.22	Roundwood (NC) → pulp, paper, printing, and publishing (RUS) → sale, maintenance, and repair of motor vehicles and motorcycles; retail sale of fuel (RUS)

Note: NC = nonconiferous; RUS = Russia; FIN = Finland.

Step 2: Construct Rows for Russian Coniferous Roundwood and Nonconiferous Roundwood Sectors

Rows representing *Russian roundwood (C)* and *roundwood (NC)* sectors show the allocation of Russian roundwood (C) and (NC) to four sectors (i.e., *mining and quarrying*, *wood and products of wood and cork*, *pulp, paper, printing, and publishing*, and *construction* sectors) of each nation in physical units. For a specific nation, we first calculate ratios by normalizing monetary flows from the Russian *agriculture, hunting, forestry, and fishing* sector to these four sectors by their sum. We then get elements indicating physical flows of Russian roundwood (C) and (NC) to these sectors of this nation by multiplying these ratios with total physical export of Russian roundwood (C) and (NC) to this nation. We also calculate related monetary values by multiplying these physical flows with prices of Russian roundwood (C) and (NC) and then deduct those monetary values from elements of the row indicating the Russian *agriculture, hunting, forestry, and fishing* sector in the WIOD. Prices of Russian roundwood (C) and (NC) are derived from the FAO FTF database (FAO 2015).

Step 3: Construct Columns for Coniferous Russian Roundwood and Nonconiferous Roundwood Sectors

Direct input coefficients of these two separated sectors are assumed to be the same as the Russian *agriculture, hunting, forestry, and fishing* sector. We can get elements in columns indicating intermediate inputs from nation-sectors to *Russian roundwood (C)* and *roundwood (NC)* sectors by multiplying those direct input coefficients with monetary values of Russian roundwood (C) and (NC) yields. Values of these two constructed columns are deducted from the column representing the Russian *agriculture, hunting, forestry, and fishing* sectors.

We made several assumptions in the construction of the MU-MRIO model because of data unavailability. In particular, we assume that direct input coefficients of these two separated

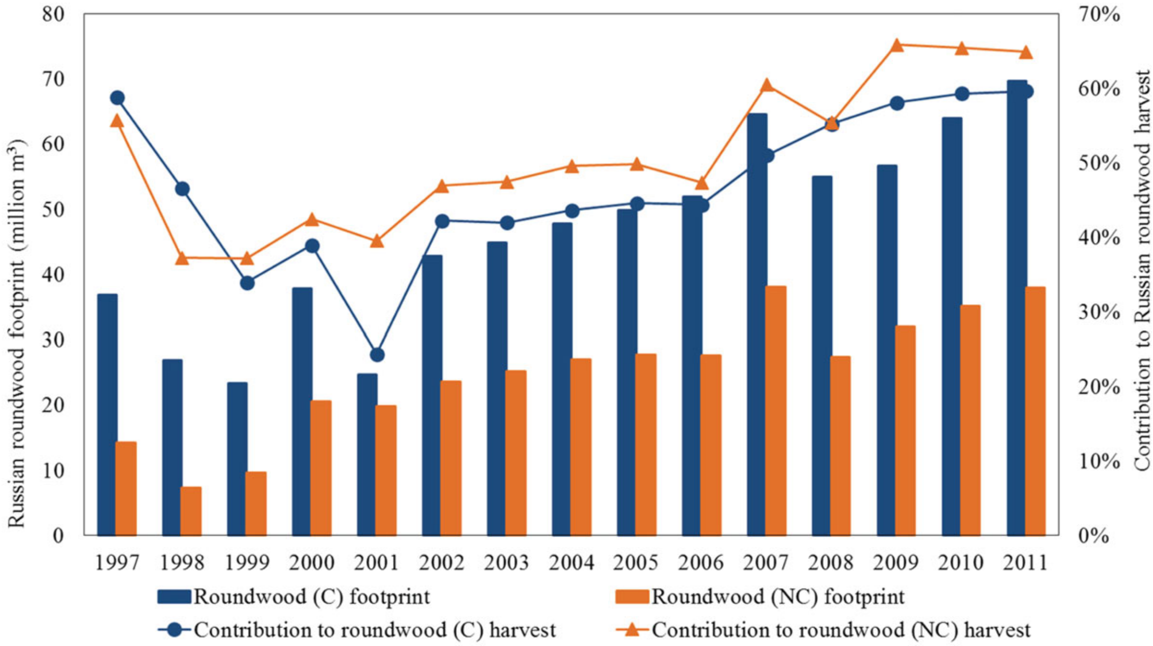

Figure 5 Time series analysis of Russian roundwood harvest caused by domestic consumption from 1997 to 2011. Detailed data are listed in supporting information table S1-5 on the Web.

sectors are the same as the Russian *agriculture, hunting, forestry, and fishing* sector. Such assumptions might bring about uncertainties to the results. Future studies should pay special attention to finding better methods or detailed data sources to improve such assumptions.

This study uses the WIOD database given its long temporal coverage and the consistency of sector classification among nations. There are additional MRIO databases, for example, Eora (Lenzen et al. 2013), EXIOBASE (Tukker et al. 2013), and GTAP (Andrew and Peters 2013). These databases are quite different from one another in many aspects (Owen et al. 2014; Arto et al. 2014; Moran and Wood 2014). Comparing global drivers of Russian timber harvest based on different MRIO databases is an interesting future research avenue.

Russian Roundwood Footprint

Russian Roundwood Footprint by Nations

Taking 2011 as the example (figure 1), Russian roundwood (C) harvest was mainly induced by the consumption of Russia (59.6%), China (13.7%), RoW (7.7%), the United States (2.8%), Japan (2.5%), and Germany (1.8%), whereas Russian roundwood (NC) harvest was mainly caused by the consumption of Russia (64.9%), RoW (8.1%), China (6.1%), the United States (2.5%), Finland (2.4%), and Japan (2.4%).

Figure 1 shows direct use (meaning directly imported amount) of Russian roundwood and the Russian roundwood footprint by nations in 2011. Domestic consumption is the largest contributor to Russian roundwood harvest. The United States does not directly import Russian roundwood, but has a large Russian roundwood footprint. China and Finland are large contributors to the direct import of Russian roundwood and the Russian roundwood footprint. China has a larger footprint than its direct import, indicating that Russian roundwood embodied in China's imports is larger than that embodied in China's exports. In addition, Japan, Germany, Italy, France, and the UK have larger footprints than their direct imports.

Per capita (cap) results in figure 2 are much different from results in figure 1. Russia has the largest per capita Russian roundwood (C) footprint (0.49 m^3/cap). Other major nations with large per capita Russian roundwood (C) footprints are Finland (0.21 m^3/cap), Estonia (0.10 m^3/cap), Lithuania (0.05 m^3/cap), and Latvia (0.05 m^3/capita). Russia also has the largest per capita Russian roundwood (NC) footprint (0.27 m^3/cap). Other major nations with large per capita Russian roundwood (NC) footprints are the Netherlands (0.13 m^3/cap), Canada (0.06 m^3/cap), Spain (0.03 m^3/cap), and Romania (0.03 m^3/cap). Large developing nations (e.g., China, India, and Brazil) usually have large populations. Although they have large amounts of Russian roundwood footprints, their per capita Russian roundwood footprints are small. On the contrary, developed nations usually have large per capita Russian roundwood footprints.

Russian Roundwood Footprint by Sectors

Figure 3 shows that Russian roundwood harvest is mainly caused by final demand in *construction*, *other manufacturing*, *educational services, health care, and social security*, *pulp, paper, printing, and publishing*, and *wholesale and retail trade* sectors globally. The *construction* sector contributes to 34.24% and

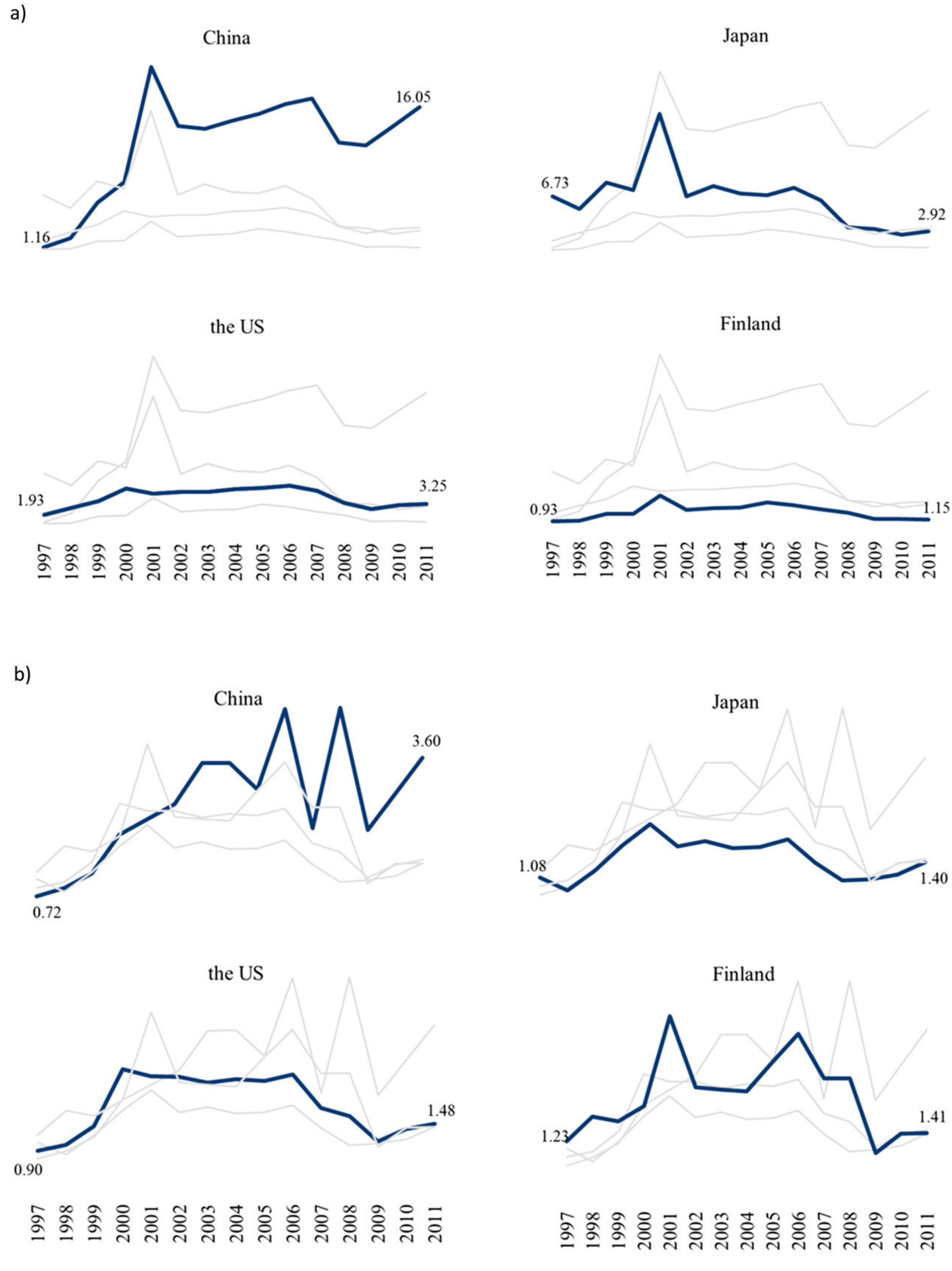

Figure 6 Time series analysis of Russian roundwood footprint of major foreign nations from 1997 to 2011 (unit: million m^3): (a) coniferous (C) and (b) nonconiferous (NC). Detailed data are listed in supporting information table S1-5 on the Web. m^3 = cubic meters.

32.3% of the harvest of roundwood (C) and (NC), respectively, in 2011. The *educational services, health care, and social security* sector directly uses few roundwood in its production, but causes large indirect roundwood uses that are embodied in its intermediate inputs from other sectors.

Russian Roundwood Footprint by Final Demand Types

Figure 4 shows that *household consumption* and *gross fixed capital formation* are two major types of final demands globally contributing to Russian roundwood harvest. *Household consumption* and *gross fixed capital formation* caused 42.2% and 40.83% of Russian roundwood (C) harvest and 44.29% and 38.28% of Russian roundwood (NC) harvest in 2011, respectively.

Major Supply-Chain Paths

Tables 1 and 2 list the top 20 supply-chain paths causing Russian roundwood (C) and (NC) harvest in 2011, respectively. Major supply-chain paths are associated with the *pulp, paper, printing and publishing* and *wood and products of wood and cork* sectors. Destinations of top 20 supply-chain paths are mainly domestic sectors of Russia, indicating that the majority of roundwood (C) and roundwood (NC) in Russia are consumed by domestic sectors. For example, total harvest of Russian roundwood (C) in 2011 is 117 million m^3, whereas only 14% is exported. Total harvest of Russian roundwood (NC) in 2011 is 59 million m^3, whereas only 7% is exported.

There are two supply-chain paths ending at China for roundwood (C): "roundwood (C) → wood and products of wood and cork (China) → other manufacturing and recycling (China)" and "roundwood (C) → wood and products of wood and cork (China)," which is consistent with the fact that China is a major direct importer and final consumer of Russian roundwood (C). There is also a supply-chain path ending at Finland for roundwood (NC): "roundwood (NC) → wood and products of wood and cork (Finland) → construction (Finland)," which is consistent with the fact that Finland is a major direct importer and final consumer of Russian roundwood (NC).

Time-Series Analysis of Russian Roundwood Footprint

Domestic consumption is the largest contributor to Russian roundwood harvest. Figure 5 shows that the amount of Russian roundwood harvest caused by domestic consumption decreased during 1997–1999 and then has been generally increasing during 2000–2011. In particular, the amount of Russian roundwood harvest caused by domestic consumption dropped in 2008 as a result of the global financial crisis. Figure 6a shows that China's Russian roundwood (C) footprint has been continuously growing since 1997 and peaked in 2001. China surpassed Japan in 2000 and became the largest foreign consumer of Russian roundwood (C). Japan shows a continuously decreasing dependence on Russian roundwood (C), especially after 2001. This is probably related to Japan's paper recycling policy. The Russian roundwood (C) footprint of the United States and major European countries are stable. Figure 6a also shows that Russian roundwood (C) footprints of major nations dropped in 2008 and 2009 as a result of the global financial crisis.

Figure 6b shows that China's Russian roundwood (NC) footprint shows an increasing trend, and China became the largest foreign consumer after 2001. Finland has the largest Russian roundwood (NC) footprint before 2001, and its Russian roundwood (NC) footprint shows a decreased trend after 2001. China surpassed Finland to be the largest foreign consumer after 2002. The United States does not have a direct import of Russian roundwood (NC), but its final consumption causes Russian roundwood (NC) harvest through global supply chains. The United States' Russian roundwood (NC) footprint peaked in 2010 as the second largest final consumer, and then shows a decreasing trend. The United States' Russian roundwood (C) footprint is relatively stable from 1997 to 2011, but its Russian roundwood (NC) footprint has significant variations in this period. Japan has a similar variation trend as the United States. Similarly, we find that Russian roundwood (NC) footprints of major nations dropped in 2009 as a result of the global financial crisis.

Table S5 in the supporting information available on the Journal's website shows that the RoW is a major contributor to Russian roundwood harvest. Disaggregating the RoW in future studies can provide more details on global drivers of Russian roundwood harvest.

Discussion and Conclusions

Existing studies have highlighted the importance of global drivers of local forest-related issues (Jonas et al. 2013; Weinzettel et al. 2013). This work investigated global drivers of Russian timber harvest during 1997–2011 by applying an MU-MRIO model. Results show that Russia, China, the United States, Japan, Finland, and Germany have large Russian roundwood footprints. Russia itself is the biggest final consumer. China is not only the most important importer of Russian timber, but also the largest foreign final consumer causing Russian timber harvest. The United States does not directly import Russian timber, but is the second largest foreign final consumer causing Russian timber harvest. Japan has a larger Russian roundwood footprint than direct import. Such findings indicate the importance of footprint accounting in analyzing Russian timber harvest. They also inform policy makers to focus on the consumption side in managing Russian forest resources, in addition to production side management of Russian forest resources.

Taking Shared Responsibilities

Taking shared responsibility is a policy option to mitigate resource use/emissions caused by international trade (Cadarso et al. 2012; Kander et al. 2015; Peters and Hertwich 2008). Negotiations among nations should be encouraged to mitigate Russian timber harvest. One possible tool is placing taxes on embodied Russian timber in international trade. How best to determine appropriate tax rates for traded products is an interesting future research avenue. Another possibility is using a certification scheme to educate consumers of final goods about the impact of their purchasing on Russian forests and climate change through global supply chains.

Improving Production Efficiency of Key Sectors in Consuming Nations

Extracted supply-chain paths show how the production of a particular sector drives Russian timber harvest. They direct the emphases for improving production efficiency of sectors in consuming nations. For example, the supply-chain path "Roundwood (NC) → wood and products of wood and cork (FIN) → construction (FIN)" identified as important implies that improving the efficiency of using Russian roundwood (NC) in the production of the *wood and products of wood and cork* sector in Finland can help reduce Russian roundwood (NC) harvest. Moreover, improving the efficiency of using inputs from the *wood and products of wood and cork* sector in the production of the *construction* sector in Finland can indirectly help reduce Russian roundwood (NC) harvest. Governments can use preferential tax rates or subsidies to encourage efficiency improvements of firms in key sectors identified in major supply-chain paths.

The analytical framework of this study can also be applied to analyze global drivers of timber harvest in other nations as well as to other resource extractions. This study links the Russian timber harvest indicator with the MRIO model. This indicator cannot capture the forest productivity and cannot trace the potential forest resource shortages. Future studies should link more forest-related indicators (e.g., forest productivity, potential forest resource shortage, and forest-related biodiversity) with MRIO models.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information S1 provides detailed data supporting the graphs in the main article. It includes five tables containing more information on the use and footprint of Russian roundwood.

Supporting Information S2: This supporting information S2 provides two tables, which give aggregation details from 35 sectors to nine sectors (table S2-1) and aggregation details from five final demand types to four final demand types (table S2-2).