Global supply chain of biomass use and the shift of environmental welfare from primary exploiters to final consumers

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Abstract

With the increasingly frequent interregional trade that leads to the geographical separation of production and consumption, the invisible shift of the environmental welfare bestowed by biomass use is brought to attention. Using a systems embodiment accounting model, this study tracked the dynamic process of interregional transfer of biomass use from primary supply to final consumption via the global supply chain. The results reveal that biomass use embodied in global trade is 87% of total global biomass exploitation. Moreover, the intermediate trade volume is 1.7 times higher than the final trade volume. In terms of biomass use, the United States, South Korea, mainland China, Japan, and the United Kingdom are revealed as the five leading net importers and also the main final consumers. Brazil, India, Cyprus, Indonesia, and Latvia are demonstrated to be the top five net exporters and also the main exploiters of biomass resources. The biomass self-sufficiency rate by source and that by sink for each country are then discussed. The outcome shows that through the channels of global supply chain, the shift of environmental welfare from biomass-exporting nations to biomass-importing

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nations occurs along with interregional trade. For Brazil and India, we suggest that they should strike a balance between economic revenues and long-term sustainability. Regarding the consumption-oriented nations such as the United States, an increase in the energy efficiency of high value-added industries is recommended.

Keywords: Global supply chain; Biomass use; Intermediate and final trade; Source-to-sink budget; Environmental welfare

1. Introduction

Faced with the grim situation of fossil-fuel depletion and environmental degradation, nations all over the world are actively exploring sustainable energy alternatives to satisfy their rising demands [1-3]. Biomass as the organic material stored in plants and animals is widely considered as a promising energy resource [4,5], and has become the fourth source of energy supply, second only to crude oil, coal, and gas [6]. According to BP [7], global biomass fuel production has nearly tripled during the last decade, rising rapidly from 2.78 million toe (tons of oil equivalent) in 2006 to 8.2 million toe in 2016. The rapid expansion of biomass exploitation has impelled the renovation of bio-energy products, such as the first generation biofuel in terms of fuel ethanol generated from food crops, the second generation represented by that generated from cellulose-based, non-edible biomass, and the third generation represented by that derived from algae [8-10]. Nevertheless, no matter it is the first, second, or third generation of bioenergy products, the cleaness is only manifested on the consumer side, while the exploitation of biomass resources are associated with environmental and socio-economic costs [11]. A displacement of the environmental welfare of biomass use may thus take place due to the separation of producers and consumers within the world market.

With the blossom of international market, bioenergy products have recently become frequently-traded commodities between world regions [12]. Matzenberger et al. [10] estimated that by 2030 the international trade volume of bioenergy products might amount to 14%-36% of the total bioenergy demand. These studies contributed significantly to uncovering the development of international trade of bioenergy products and providing valuable future perspectives for biomass trade using empirical data. Nevertheless, it is also noticed that these researches eyed only on the international trade flows of biomass products and did not consider the biomass use embedded in the non-biomass products traded. However, not only the bioenergy products but also non-biomass goods may lead to the displacement of biomass resources due to the interconnections of the industries [13]. In the world economy, once the natural biomass resources are exploited, the use of the biomass resources comes into the economy. The biomass use is transferred with value flows along the global supply chain via interregional trade, which supports the production of not only bioenergy products but also all the other commodities in the economic network [14]. In this sense, the bio-fuel products are only commodities out of the economical use of genuine biomass resources, which are similar to all other output products from different economic sectors. All the products within the economic network serve the embodiment of biomass use. Therefore, the use of biomass resources could be invisibly transferred to foreign regions via international trade of both bioenergy and non-bioenergy products.

Currently, the economic boundary between regions is becoming obscure as countries and regions in the world have been linked closely by an economic network highlighted by highly frequent trade flows [15,16]. Differing from early times where the traded products are mainly for consumptive purposes, currently, the majority of imported products from foreign countries are used as intermediate inputs to produce new goods or as re-exports instead of being directly consumed [17-19]. Taking China for instance, it specializes in processing trade and imports a great quantity of raw materials and spare parts to produce mechanical products and other finished goods for exports. As a result, intermediate products are taking a more and more important role in the global supply chains [20]. Existing statistics reveal that intermediate trade is accountable for two-thirds of the total volume of international trade [21]. In such a globalized world economy with complex intertwined trade connections, the use of biomass resources disperses into the whole economic network via global supply chains and may flow across several nations before it finally sinks into the goods or services used as final consumption. It is therefore essential for us to explore the biomass use hidden in both intermediate and final trades to investigate the flows of biomass use between regions, instead of simply assigning biomass consumption to the final consumers as the responsible agents [22]. In a highly interconnected world economy, genuine biomass exploiters do not act as consumers most of the time. As international trade realizes the geographical splitting of production and consumption activities [23,24], the environmental welfare bestowed by the use of biomass resources could be invisibly transferred between biomass-importing countries and biomass-exporting countries via interregional trade [11]. Therefore, it is necessary to explore who acts as exploiters and who acts as consumers in terms of biomass use to balance the socio-economic benefits and environmental welfare.

At present, several studies have been undertaken to explore resource use embedded in international trades using a global perspective, such as carbon emissions [25-27], energy[28,29], land [30], and water [31]. In particular, a steady flow of academic works explored the total energy use [13], crude oil use [32], coal use [33], and natural gas use [34] in international trade flows via global supply chains using a source to sink manner. Regarding biomass, a number of studies have adopted the concept of HANPP (embodied human appropriation of net primary production) to estimate the geographical disconnection of biomass exploiters and consumers induced by international trade [35-37]. Erb et al. [38] depicted the upstream withdrawal of biomass resources induced by the consumption of internationally-traded bio-products and the associated impacts on ecosystems, using the concept of HANPP. Saikku and Mattila [39] used HANPP to trace the biomass use induced by traded biomass products of Finland from 2000 to 2010, revealing Finland as a notable importer of embodied HANPP. These pioneering works offer valuable insights into the virtual biomass use transfer between regions via international trade of bio-products. Nevertheless, biomass use is induced along the supply chains of bio-products as well as any other kind of products. It is imperative to trace the biomass use embodied in global supply chains from source of exploitation to sink of final consumption to get a panorama of the shift of environmental welfare associated with biomass resources between regions in the global economic network.

This study is to provide a comprehensive view of the international flows of biomass use from the source of exploitation to sink of final consumption from an embodiment perspective. The role of international trade in distributing the environmental welfare associated with biomass resources will be specifically focused on. The remainder of this paper is structured as follows: Section 2 describes the methodology and data source. Section 3 displays the main results for trade flows of biomass use between regions along the global supply chain. Section 4 establishes a source-to-sink budget of biomass use and the shift of environmental welfare from primary exploiters to final consumers in terms of biomass use. Conclusions are drawn in Section 5.

2. Methodology and data source

2.1. Embodiment accounting model for the global economy

The embodiment accounting model is applied in this study to investigate the dynamic process of interregional transfer of resource use for the global economy. To simulate the interregional flows of goods within the world economy, the global multi-regional input-output table (MRIO) that can effectively reflect the interdependence among sectors in different regions of the world is adopted as a supporting tool. The world is simulated as containing a number of a regions, and each region is made up of b basic economic sectors. Taking Region m's Sector i as an example, the balance of resource use flow is illustrated in Figure 1. e_i^m stands for the genuine resources exploited from environment as external inputs into Region m Sector i; p_i^m is the primary inputs (such as consumption of fixed assets, etc.) from the society to Region m Sector i; t_{ji}^{nm} represents the economic flows from Region n Sector j to Region m Sector i in monetary terms, namely the intermediate inputs of Region m Sector i offered by Region n Sector j. f_i^{mn} represents the economic flows of final demand from Region m Sector i to Region n, namely the final products provided by Region m Sector i for Region n, which are comprised of two parts[1]: f_{iC}^{mn} and f_{iK}^{mn}. f_{iC}^{mn} is the part of final products used for final consumption, while f_{iK}^{mn} is the part of final products used as capital goods. ε_i^m denotes the resource intensity of products produced by Region *m* Sector *i*; ε_p denotes the intensity of primary inputs. It needs to be noted that in some previous studies, it is treated that products used for final demand are the ultimate sink of resource use. However, final demand is a large pool comprising several agents, such as final consumption by households, that by non-profit organizations serving households, that by government, gross fixed capital formation, and inventory change. It is reasonable to treat the products used for final consumption by households, non-profit organizations and government as the ultimate sink of resource use since these products are genuinely consumed. Just as claimed by Adam Smith [40], consumption serves the only destination of all production. Regarding products used for gross fixed capital formation and inventory increase, they fall into the category of final demand but are not used for final consumption: they are reallocated within the economic network and are supposed to sustain the production activities further.

The balance of resource use flow can be expressed as:

$$e_i^m + \varepsilon_p p_i^m + \sum_{n=1}^{a} \sum_{j=1}^{b} \varepsilon_j^n t_{ji}^{nm} = \varepsilon_i^m y_i^m, \quad (1)$$

$\sum_{n=1}^{a} \sum_{j=1}^{b} \varepsilon_j^n t_{ji}^{nm}$ represents the total resource use embodied in the intermediate inputs of Region *m* Sector *i*; $\varepsilon_p p_i^m$ represents the total resource use embodied in the primary inputs of Region *m* Sector *i*; $\varepsilon_i^m y_i^m$ represents the total resource use embodied in output products of Region *m* Sector *i*.

The matrix form of Eq. (1) can be derived as:

$$E + \varepsilon_p P + \varepsilon T = \varepsilon \hat{Y}, \quad (2)$$

[1] The final demand category consists of final consumption expenditure by households, that by non-profit organizations and government, together with the gross fixed capital formation and changes in inventories and valuables. Final consumption is comprised of the three consumptive agents mentioned above, which are taken here as the sink of resource use.

in which $\mathrm{E} = [e_i^m]_{1\times ab}$; $\mathrm{P} = [p_i^m]_{1\times ab}$; $\mathrm{T} = [t_{ji}^{nm}]_{ab\times ab}$; $\varepsilon = [\varepsilon_j^n]_{1\times ab}$; $\hat{\mathrm{Y}}$ is the diagonal matrix deduced by $\mathrm{Y}(= [y_i^m]_{1\times ab})$; $\varepsilon_p = [\varepsilon_p]_{1\times 1}$. ε_p is a scalar and it is assumed to be the same in different sectors since the corresponding redistribution matrix for the global input-output table is unknown to us [41].

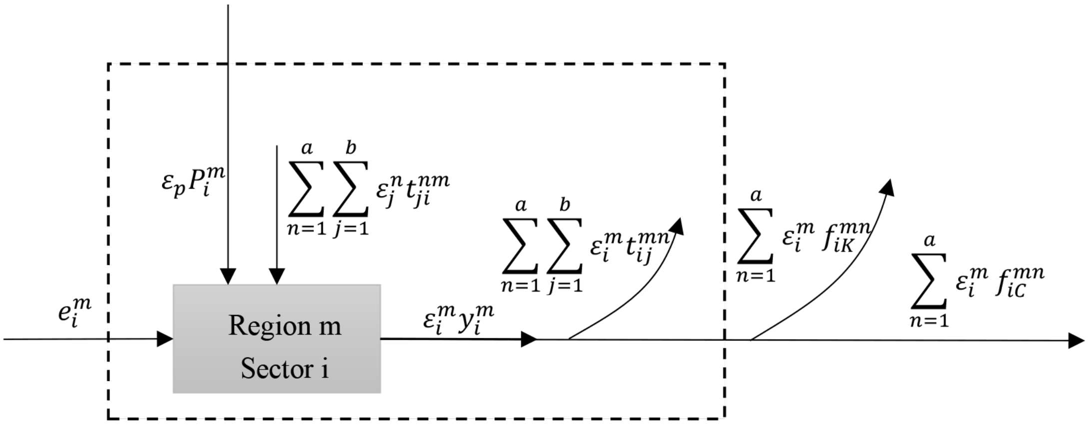


Figure 1. The balance of biomass use flows for an economic sector

The embodiment accounting model used in some previous studies pays attention only to the resource use associated with intermediate inputs but excludes the external feedbacks associated with primary inputs, thus failing to maintain the circulation loop. In the embodiment accounting model used in this study, resource use embodied in the primary and intermediate inputs are both considered. For the world economy that is simulated by the global multi-regional input-output account, an overall balance is that the monetary value of the intermediate inputs and that of the primary inputs is equal to the summation of the monetary value of the output products for intermediate use and that of the output products for final demand. The biophysical balance associated with the overall monetary balance has already been depicted by Equation (2). Meanwhile, For the output products used as final demand, those used for final consumptive activities (such as household consumption, government consumption and non-profit consumption) can be regarded as genuinely consumed, while the capital goods (namely the final products used for non-consumptive purposes) circulate from the final demand quadrant into the quadrant of primary inputs to support the economic production. Hence, we can get another biophysical balance: resource use embodied in primary inputs is equal to that in capital goods [42, 43]. The balanced equation can be established:

$$\varepsilon_p \sum_{m=1}^{a} \sum_{i=1}^{b} p_i^m = \sum_{m=1}^{a} \sum_{i=1}^{b} \sum_{n=1}^{a} \varepsilon_i^m f_{iK}^{mn}. \quad (3)$$

The corresponding matrix form is obtained as:

$$\varepsilon_p P_{sum} = \varepsilon F_K, \quad (4)$$

in which the expression on the left side is the sum of resource use embodied in primary inputs, and that on the right side is the sum of resource use embodied in capital goods. By combining Eqs. (2) and (4) can we get the equation of embodied resource intensity matrix:

$$\varepsilon = \mathrm{E}[\widehat{\mathrm{Y}} - T - (1/P_{sum})F_K P]^{-1}. \quad (5)$$

The resource use embodied in products used as final consumption (*REC*) of Region *m* can be thus calculated as:

$$REC^m = \sum_{n=1}^{a} \sum_{j=1}^{b} \varepsilon_j^n f_{jC}^{nm}. \quad (6)$$

Beisdes, it is worth noting that for the global economy, an overall balance is that the sum of *REC* for all regions as the sink is equal to the sum amount of resource directly exploited from natural environment (*RE*) as the source, which is presented as:

$$\sum_{m=1}^{a} REC^m = \sum_{m=1}^{a} \sum_{i=1}^{b} e_i^m. \quad (7)$$

The trade patterns, namely resource use embodied in imports (*REI*) and that in exports (*REE*) are also analyzed here. Meanwhile, interregional trade is categorized into intermediate trade and final trade. The two trade patterns can be illustrated as：

$$REI^m = \sum_{n=1(n\neq m)}^{a} \sum_{j=1}^{b} \left[\sum_{i=1}^{n} \left(\varepsilon_j^n t_{ji}^{nm}\right) + \varepsilon_j^n f_j^{nm}\right], \quad (8)$$

and

$$REE^m = \sum_{i=1}^{b} \sum_{n=1(n\neq m)}^{a} \left[\sum_{j=1}^{n} \left(\varepsilon_i^m t_{ij}^{mn}\right) + \varepsilon_i^m f_i^{mn}\right]. \quad (9)$$

The trade balance of resource use can be thus derived as:

$$REB^m = REI^m - REE^m. \quad (10)$$

The region with a positive REB is a net importer, while that with a negative REB is a net exporter.

2.2. Data source

Existing transnational input-output databases mainly include WIOD (world input-output database), Eora, OECD, and GTAP. Compared with other input-output databases, the advantages of WIOD reside with the high data quality and consistency with the international trade statistics. Therefore, in this study the global MRIO table taken from WIOD is applied, which is updated to the year 2014. This database divides the world economy into 44 regions (including the rest of the world as an aggregated region), and each region consists of 56 sectors. Altogether, the trade flows of 2464 production units are incorporated in the global MRIO table. Appendix A and B present the names of regions and a concrete classification of sectors, respectively. The biomass exploitation for each region within the world economy is obtained from the sheet of energy balance flows provided by IEA (International Energy Agency). Besides, the population of each region is taken from the World bank.

3. Results

3.1. Biomass use of each region

Biomass use embodied in global final consumption is calculated to reach up to 1303 million toe, equal to the biomass exploitation. Figure 2 presents the biomass use embodied in final consumption and biomass exploitation of each region. The numerical values are given in Appendix C. The index of biomass exploitation can be seen as the environmental welfare endowed by the local ecosystem, while biomass use embodied in final consumption is a final-consumer-based index that represents biomass use induced in the global supply chain by the region's final consumption. As illustrated in Figure 2, biomass use and exploitation of a region are not completely related, as regions could meet their consumptive demands through the interregional trade of biomass use. Taking the United States for instance, the biomass use embodied in its final consumption is nearly 1.53 times larger than its biomass exploitation. For Ireland, South Korea, Taiwan Province, the United Kingdom, and Malta, they have a similar economic structure, whose biomass use turns out to be larger than biomass exploitation. For mainland China, Brazil, and Indonesia, on the contrary, biomass exploitation is higher that embodied in their final consumption. As to the indirect feedback of the economy in terms of biomass use, the amount of biomass use embodied in the intermediate inputs is evidently larger than that embodied in the primary inputs.

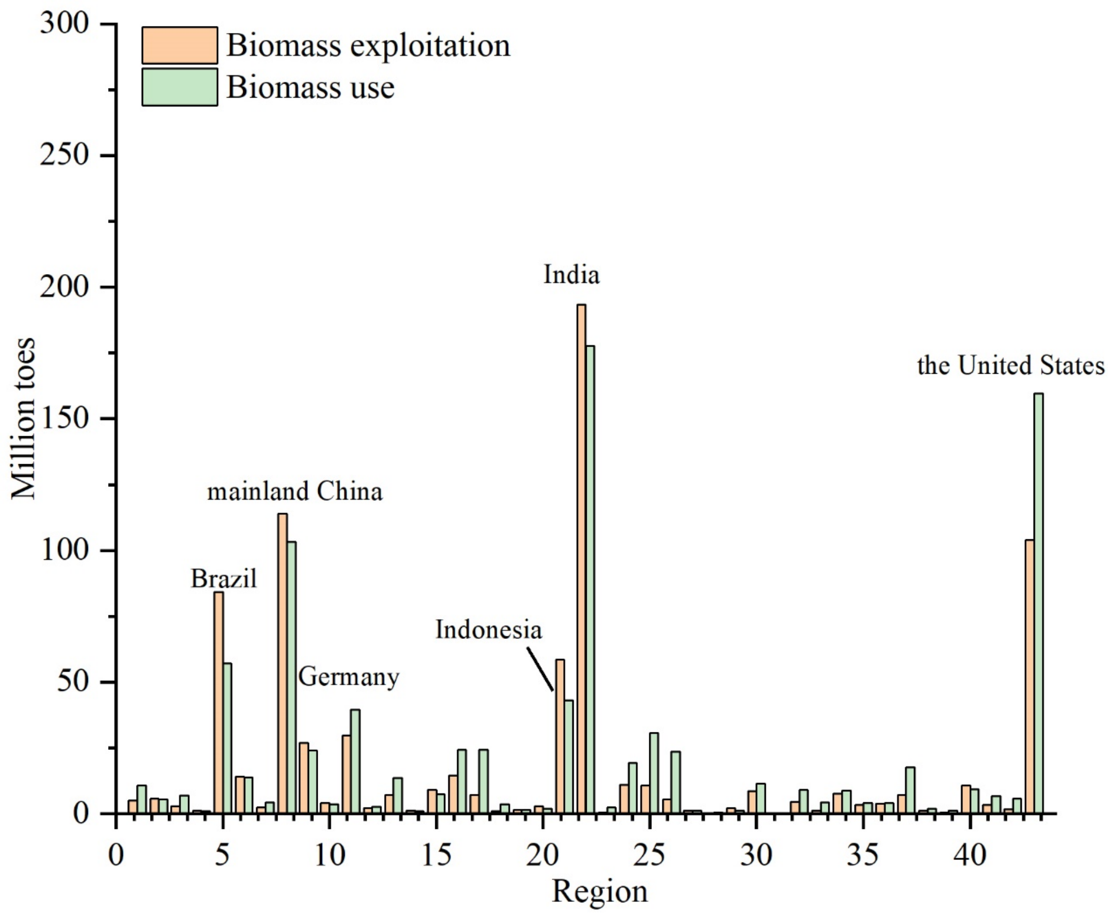


Figure 2. Biomass use and direct exploitation for each region

Figure 3 describes per-capita biomass use embodied in final consumption of 43 regions (not including the rest of world) and the world average level. For most regions, per-capita biomass use is higher than the world average (0.173 toe/capita). Though, we can still see the big divergence in per-capita biomass use of different regions. The regions with high level of per-capita biomass use are mostly in Europe, especially the EU. The largest per-capita biomass use (20.9 toe/capita) resides with Cyprus, followed by Finland, Sweden, Luxembourg, Norway, and Estonia. In the 43 regions, there are 7 regions whose per-capita levels are lower than the world average, such as mainland China (0.076 toe/capita) and Turkey (0.086 toe/capita). In particular, it is worth noticing that per-capita biomass use in China is far less than the world average, even lower than the level of populous countries like India and Indonesia.

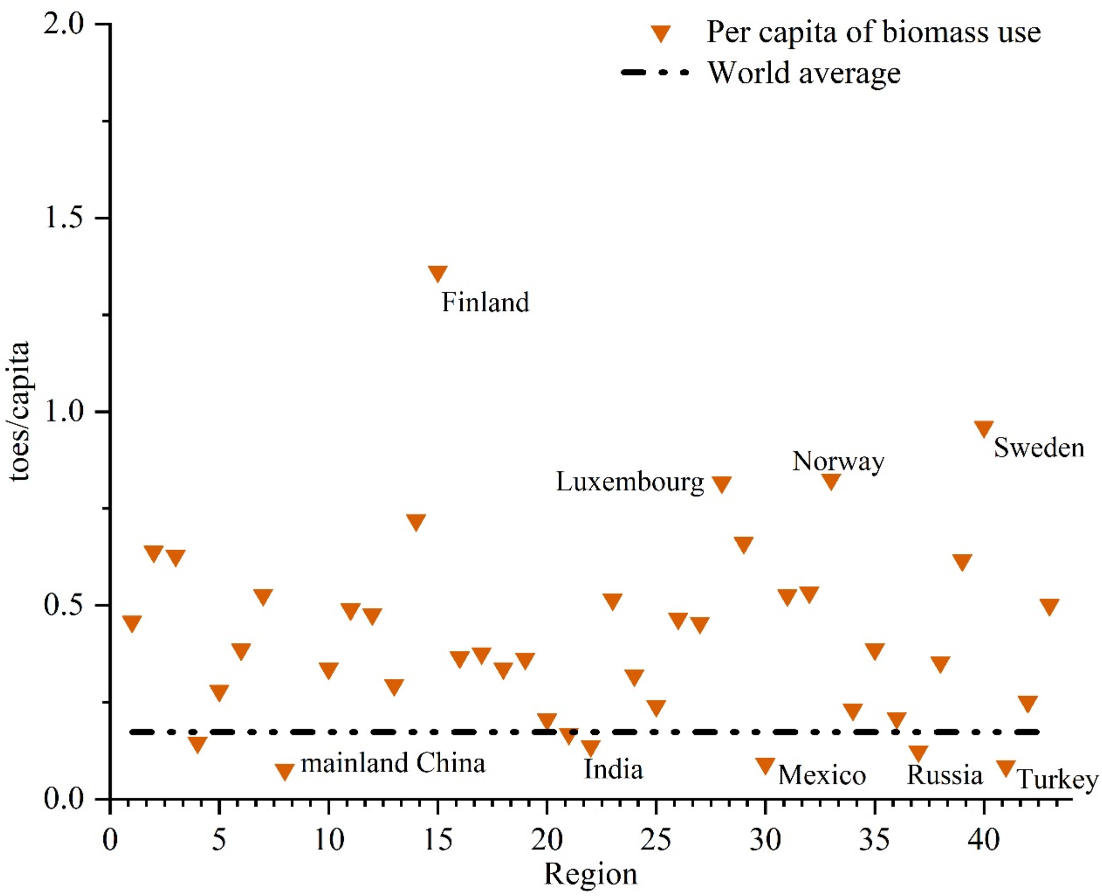


Figure 3. Per-capita biomass use of each region

3.2. Biomass use embodied in trade

The world economy is highlighted by not only the separation of production and consumption but also the fragmentation of the production processes. In this regard, it is necessary to explore the biomass use embodied in both intermediate and final products to get a comprehensive understanding of the interregional transfer of biomass use. Figure 4 depicts the trade structure in terms of biomass use for the 43 nations and regions (ROW not included). The total volume of biomass use embodied in import of all regions is equal to that in export, which amounts to 1129.5 million toe that is 87 % of the global exploitation of biomass resources (see Appendix C). Meanwhile, the intermediate trade volume in terms of biomass use is revealed as 1.6 times higher than the final trade volume, suggesting the intricacy of the global supply chain. As shown, the largest five importers of biomass use are the United States, mainland China, Germany, South Korea, and Japan, respectively. Regarding exports in terms of biomass use, the United States is the largest exporter with 29.55 million toe, closely followed by Brazil, Germany, mainland China, and India.

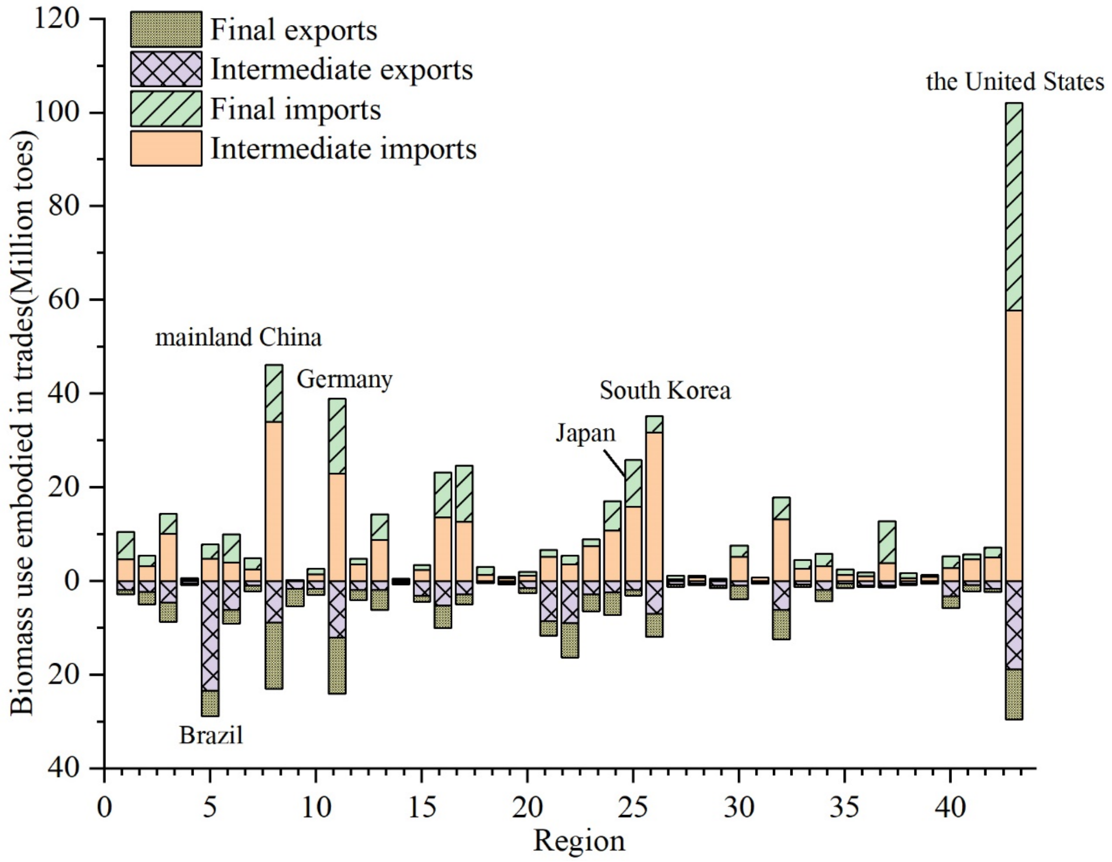


Figure 4. Biomass use embodied in trade

Meanwhile, the biomass use embodied in net trade is depicted in Figure 5. The United States, South Korea, mainland China, Japan, and the United Kingdom are the five largest net importers who benefit from international trade in terms of biomass use.

Among the 43 regions, eleven of them are net exporters of biomass use. Brazil, India, Cyprus, Indonesia, and Latvia are the top five net exporters. In particular, for Brazil, that is rich in biomass resources, its export of biomass use is much higher than that of other regions.

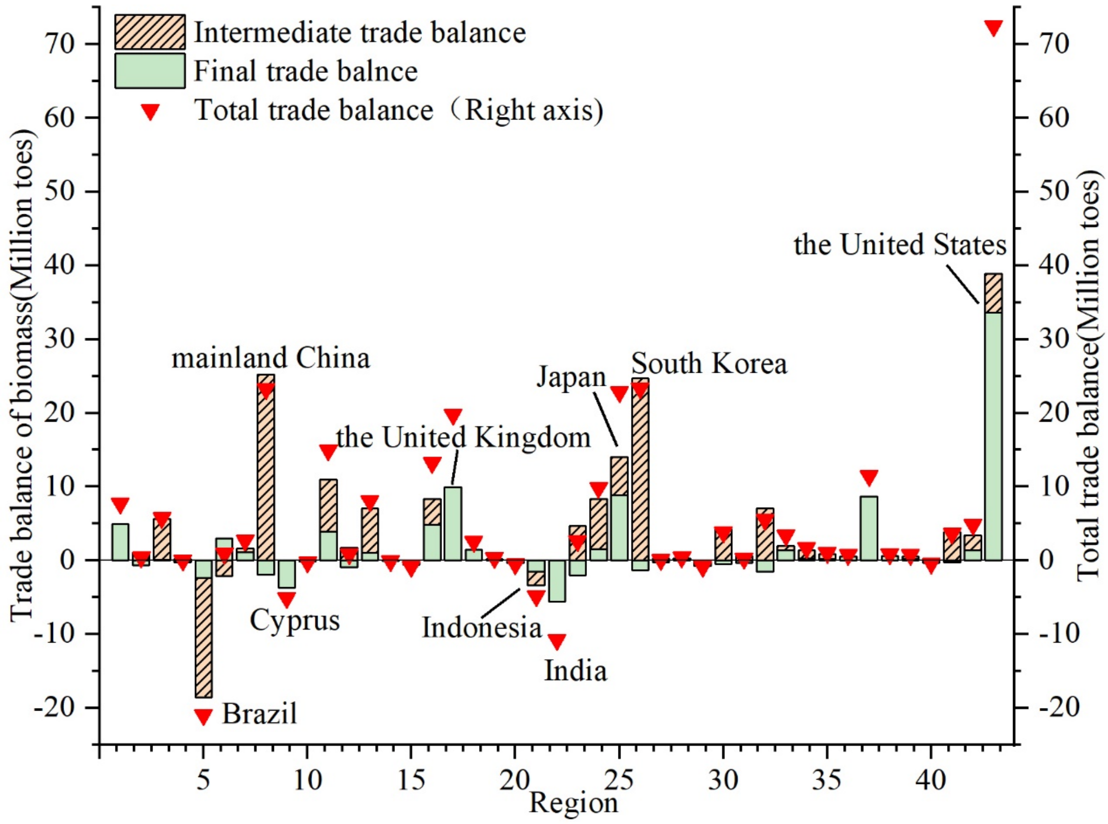


Figure 5. Biomass use embodied in trade balance

Figure 6 and Figure 7 respectively give the sectoral profile of the intermediate and final trade volume of the top five net importers and five exporters. Appendix D gives the sectoral classification. It is noticed that *Service* industry accounts for a significant proportion (72%) of the United States' imports of biomass use, suggesting the high reliance of the United States economy on the tertiary industry. Meanwhile, among all *Service* sectors, *Advertising and market research* contributes the biggest share. South Korea, Japan, and Germany have the same importing structure, whose imports of service products respectively occupy 83%, 36%, 46% of their imported biomass use. Mainland China is different from these regions in that its agricultural imports account for a notable proportion in its intermediate imports of biomass use, reaching up to 63%. Also, agricultural industry contributes 82%, 59%, 73%, and 69% to the intermediate exports of Brazil, India, Canada, and Cyprus in terms of biomass use. For Indonesia, exported food products take up the largest share (60%).

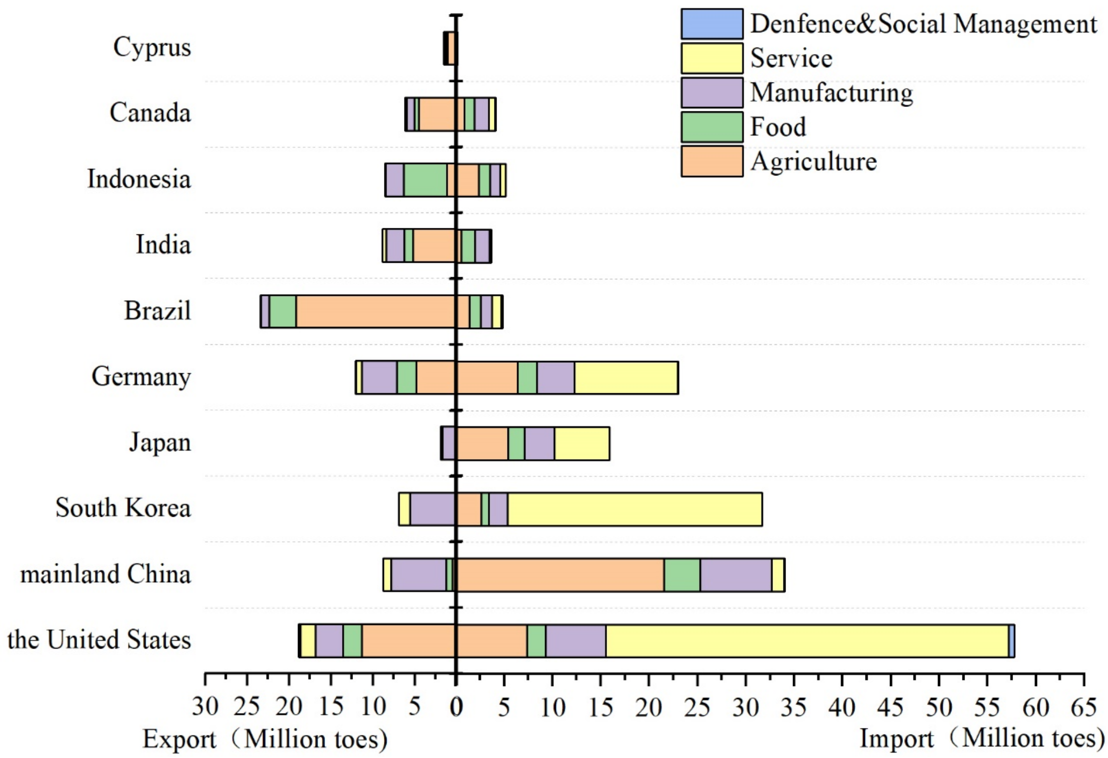


Figure 6. Sectoral contributions to intermediate trade of the top five net importers and five exporters

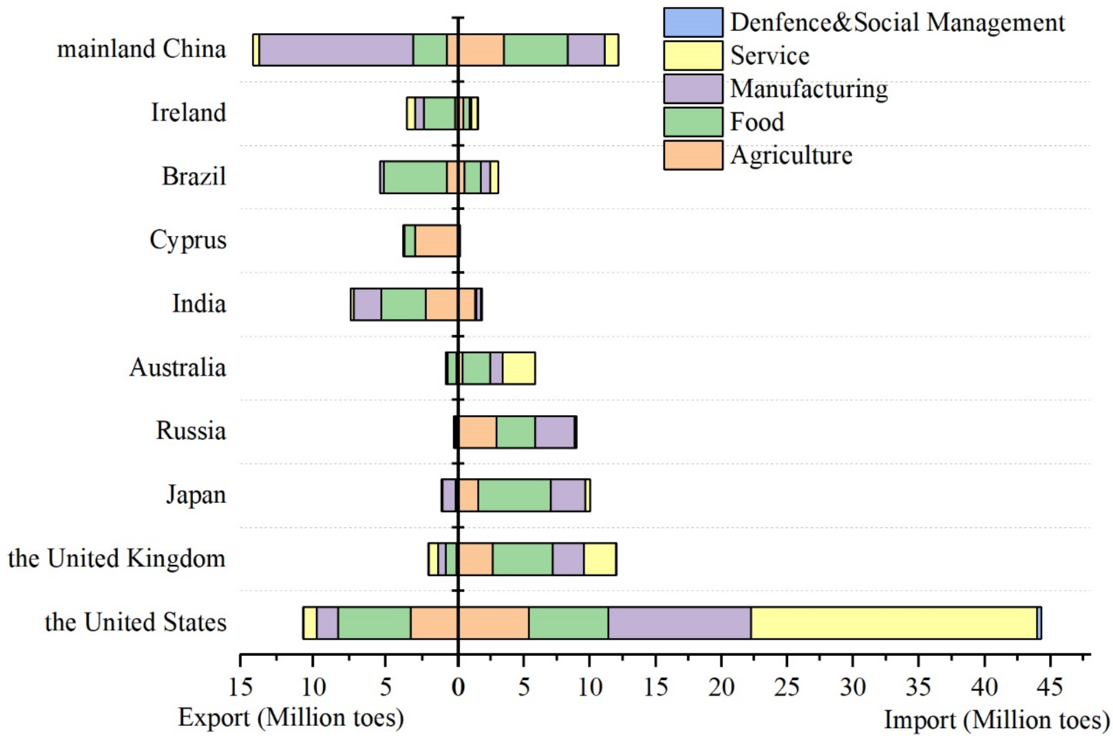


Figure 7. Sectoral contributions to final trade of top five net importers and five net exporters

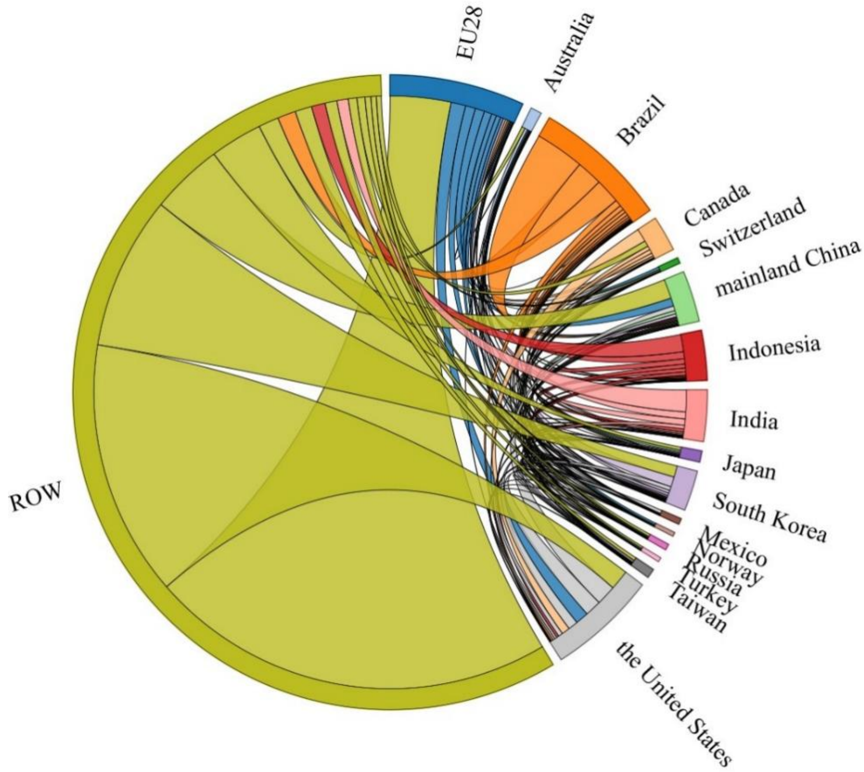
As for final trade of biomass use, imported *Service* products account for 49% of the United States' final imports. For Australia, imports of *Service* products hold accountable for 42% of its final imports. The United Kingdom has a relatively averaged importing structure of biomass use. *Agriculture*, *Food*, *Manufacturing*, and *Service* products take up 21%, 38%, 20%, and 20% of its imports, respectively. For Cyprus, Brazil, and mainland China, the shares of the *Agriculture, Food and Manufacturing* in the total final exports are respectively 78%, 80%, and 75%. This has to a certain extent reflected the dependence of these regions on agricultural and manufacturing industries.

3.3. Trade connections between major economies in terms of biomass use

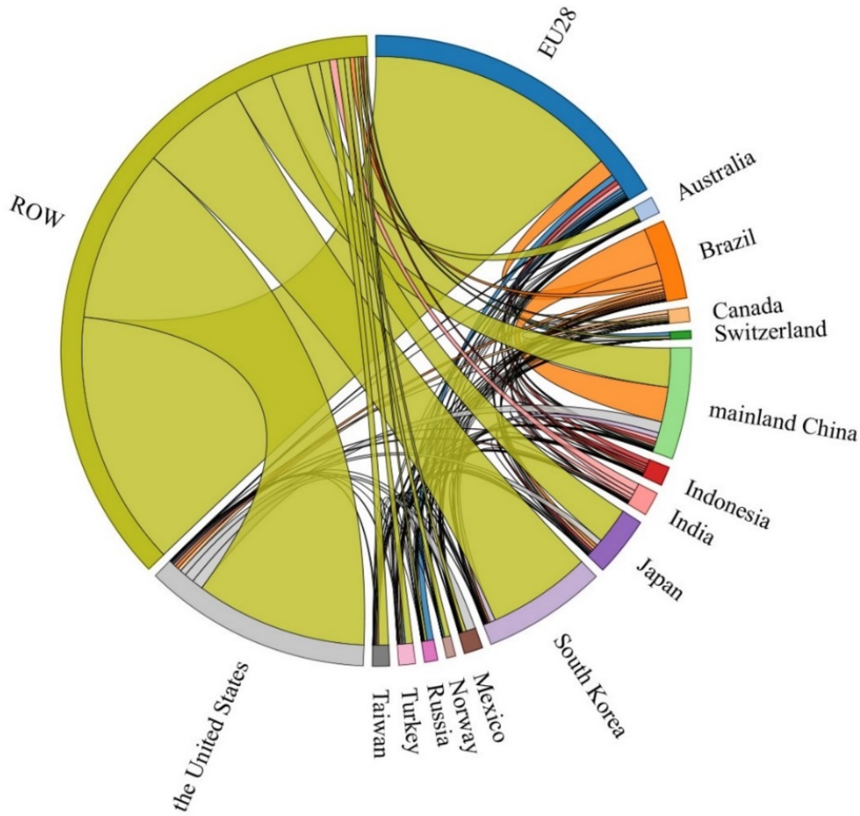
Figure 8 and Figure 9 respectively manifest the intermediate trade and final trade connections in terms of biomass use for several major regions. The regional classification is mainly consistent with the WIOD, except that the 28 members of the European Union are integrated into one region, namely EU28. Therefore, the whole world is divided into seventeen (including the rest of the world, i.e. ROW) regions. The trade volume (including both intermediate and final trades) in terms of biomass use corresponds to the size of the fan-sector. The chord connecting every two regions represents the bilateral trade (intermediate and final) relation between economies.

Figure 8(a) illustrates the relations between the seventeen regions in intermediate trade of biomass use. As depicted, the ROW (the constituents of which are mainly developing or less developed regions) is the biggest exporter among all the economies. The largest flow is from the ROW to EU28, reaching 75.29 million toe, which is 38% of the ROW's exports in terms of biomass use. The United States, second to EU28, receives 47.31 million toe from the ROW, which takes up 81% of all its imports. EU28 is the second biggest exporter, 48% of whose products flow to the ROW. Brazil is also a big exporter, which exports most of its products to mainland China, EU28, and the ROW. For mainland China, its intermediate imports of biomass use are mainly coming from the ROW, Brazil, and the United States.

The relations between the seventeen regions in net intermediate trade are portrayed in Figure 8(b). As could be seen, several notable net intermediate bilateral trades occur between EU28 and the ROW, the United States and the ROW, Brazil and mainland China, and South Korea and the ROW. The ROW is the biggest net exporting region, which gains a big surplus in trade with the other regions except for Brazil, Indonesia, and India. Brazil, the United States, and India are also notable net exporters in the net intermediate trade of biomass use. Specifically, Brazil is the biggest contributor to China's imports of biomass use. For the United States, its biggest three net receivers of biomass use are China, Mexico, and Japan. China is a net importer in trade relations with most regions, especially with the ROW and Brazil.


EU28
Australia
Brazil
Canada
Switzerland
mainland China
Indonesia
India
Japan
South Korea
Mexico
Norway
Russia
Turkey
Taiwan
the United States
ROW

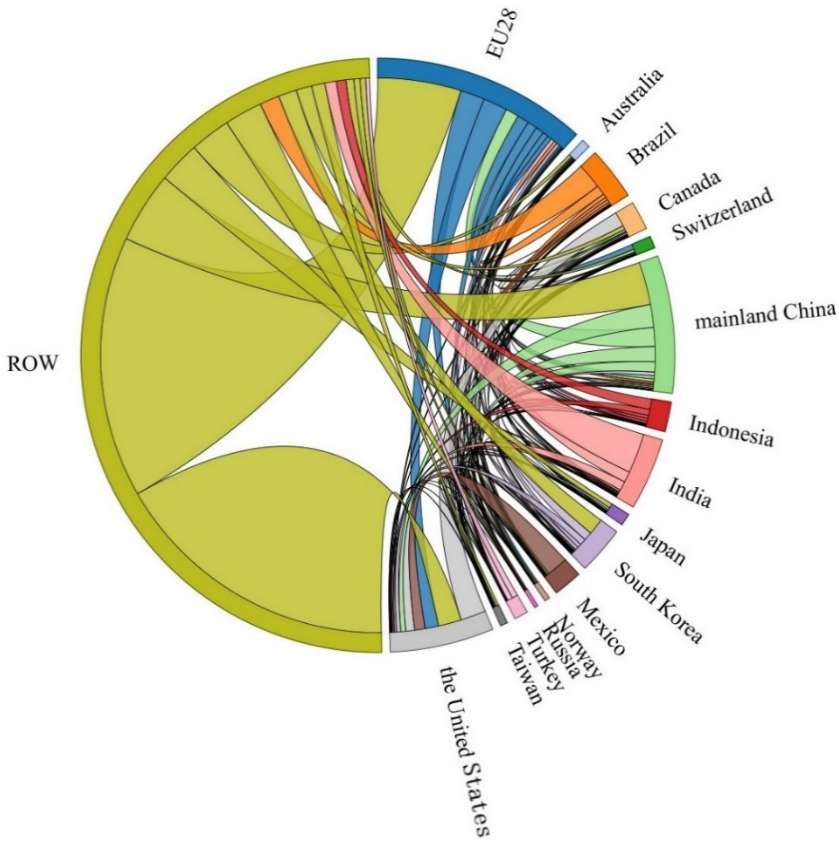
(a)


EU28
Australia
Brazil
Canada
Switzerland
mainland China
Indonesia
India
Japan
South Korea
Mexico
Norway
Russia
Turkey
Taiwan
the United States
ROW

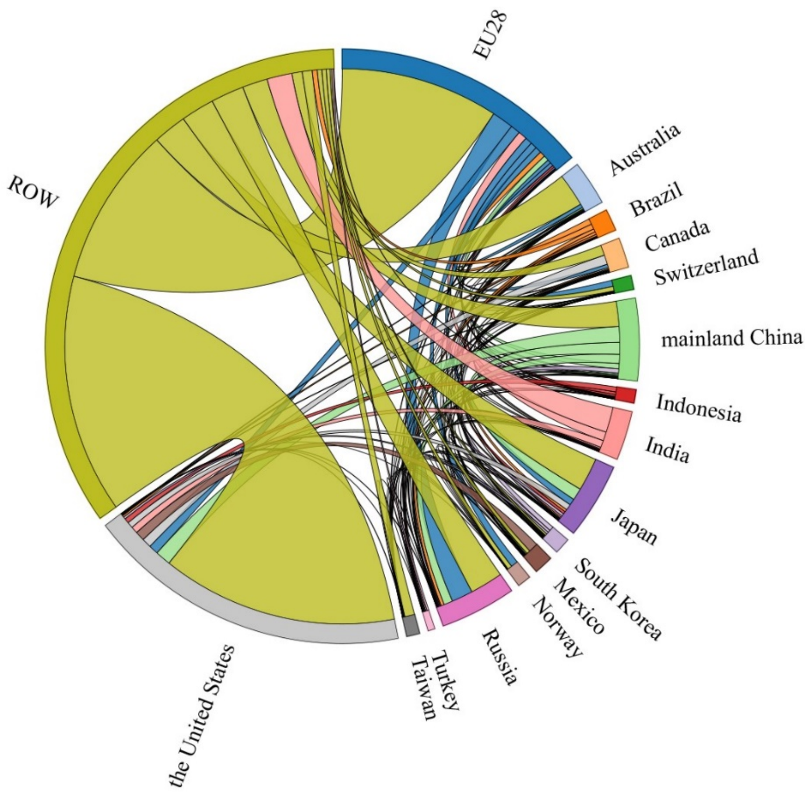
(b)

Figure 8. Inter-regional biomass use between 17 economies in (a) intermediate trade and (b) net intermediate trade

Figure 9(a) depicts the relations between the seventeen regions of in final trade in terms of biomass use. The ROW is still the biggest exporter, while the United States is the biggest importer. The flow of biomass use from the ROW to the United States stands out with 31.92 million toe, closely followed by that from ROW to EU28. EU28 is the second biggest exporter whose exports mainly flow into the ROW, the United States, and Russia. Mainland China ranks the third among these regions in final exports of biomass use, whose main destinations are the ROW, the United States, and EU28. For the intermediate imports of the United States, around 72% of them are from the ROW, 6% from EU28, and 6% from China. The ROW also acts as an important receiver in intermediate trade with EU28, China, and India.



(a)



(b)

Figure 9. Trade relations in terms of biomass use between 17 economies in (a) final trade and (b) net final trade

The bilateral net final trade relations of the seventeen regions are revealed in Figure 9(b). With regard to the net final trade of biomass use, the ROW, India, and Brazil are major net exporters, while the United States, EU28, Japan, and Russia are notable net importers. The notable flow of biomass use in net final trade is from the ROW to the United States and the ROW to EU28. Mainland China is a prominent contributor to the net final imports of the United States, Japan, Russia, and EU28, respectively reaching an amount of 1.93 million toe, 1.48 million toe, 1.09 million toe, and 0.64 million toe.

3.4. Biomass exploiters and consumers by a source-to-sink manner

Biomass exploitation and biomass consumption respectively represent the source and the sink of biomass use. The genuine biomass exploiters are the nations where biomass exploitation occurs. The biomass consumers are taken as the nations where final consumption (household consumption, government consumption, and non-profit organization consumption) takes place. A source to sink budget is established in this section to explore how the use of biomass resources exploited eventually sinks into final consumption, as illustrated in Figure 10.

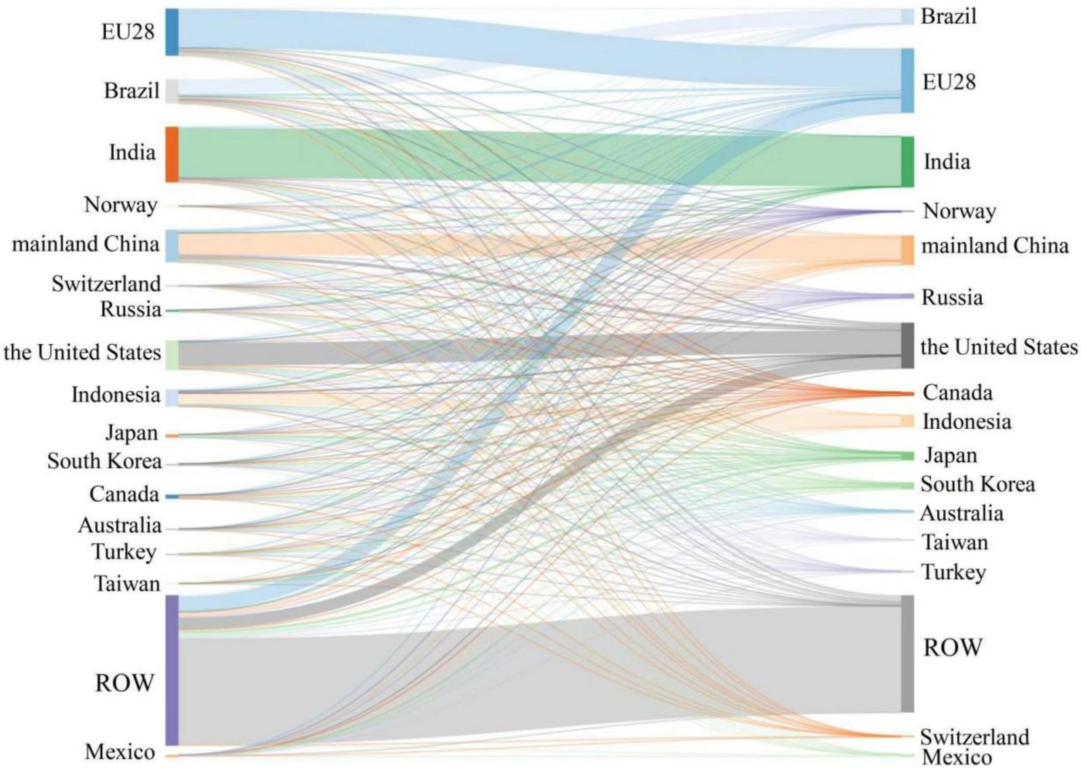


Figure 10. A budget for biomass use from source of exploitation to sink of final consumption

As witnessed, EU28 serves as a notable biomass exploiter and also a biomass consumer. For EU28 as a sink of biomass use, biomass use embodied in its final consumption is in magnitude 1.4 times of its biomass exploitation. Around 40% of EU28's final consumption in terms of biomass use originates from foreign regions. Meanwhile, around one-fifth of EU28's biomass exploitation is finally enjoyed by foreign nations represented by the United States, Russia, and China. For the United States, it is illustrated to be a notable final consumer and importer, the biomass use sinking into whose final consumption is in magnitude 1.5 times as much as its biomass exploitation. Only half of the United States' final consumption of biomass use is denoted by domestic biomass exploitation, and the rest mainly stems from China, EU28, Indonesia, and Brazil. As for Brazil, it is highlighted as a main biomass exploiter and exporter. Around 40% of Brazil's biomass exploitation is eventually sinking into the goods and services used for final consumption of foreign nations represented by EU28, China, and the United States.

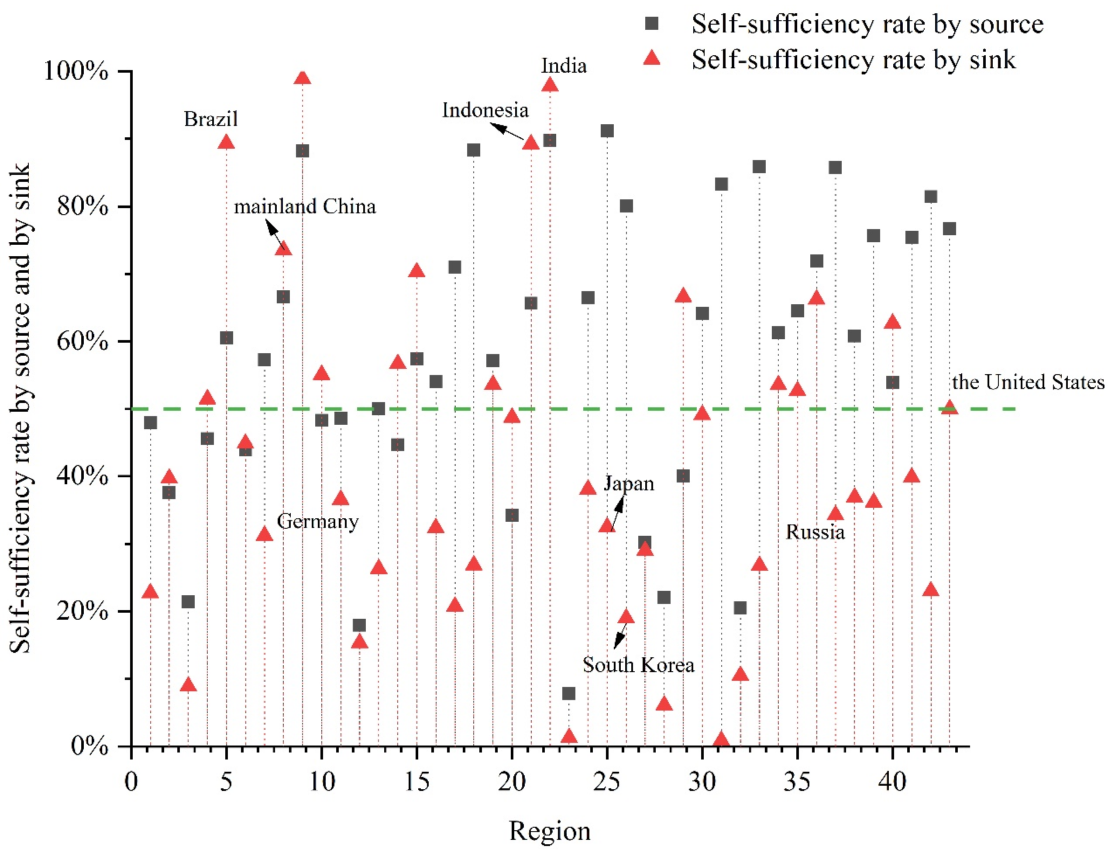


Figure 11. Self-sufficiency rate by source and that by sink

Meanwhile, the indices of biomass self-sufficiency by source and that by sink (source to sink budget) are calculated in this section, which is illustrated in Figure 11. For many regions, the biomass use embodied in final consumption is mainly from foreign regions. It can be seen in the figure that the self-sufficiency rates by source for many regions are over 50%. In contrast, in terms of the self-sufficiency rate by sink, most regions lie below the diagonal line. This means that the majority of local biomass exploitation is eventually consumed by itself, while only a small part of biomass use embodied in final consumption originates from itself. For India, the local biomass exploitation is finally sinking into the goods used for India's domestic final consumption. Meanwhile, India's final consumption in terms of biomass use mainly originates from itself, which is characterized as a typical self-sufficient and self-contained society. While for Japan, though domestic exploited biomass resources are mostly being kept at home, around two-thirds of its biomass use embodied in final consumption originate from foreign regions. It can be concluded that Japan as a country with limited resources, acts as a prominent consumer in the global supply chain. Brazil and Indonesia have notably high self-sufficiency rates by sink (around 90%), whose biomass use mainly comes from domestic exploitation. Russia, South Korea, and the United States have relatively high self-sufficiency rates by source. It suggests that nearly four-fifths of their biomass exploitation are finally sinking the goods and services used to meet their own final consumption. Nevertheless, their self-sufficiency rates by sink vary greatly. South Korea's self-sufficiency rate by sink is 19%, obviously lower than that of Russia and that of the United States. It means that over four-fifths of the biomass use induced by South Korea's final consumption are from other regions via the global supply chain. For China, its self-sufficiency rate by source and that by sink are respectively 67% and 74%. It could be seen that mainland China acts as a producer rather than a consumer in the global supply chain in terms of biomass use.

4. Discussions

4.1. Roles of regions in international trade of biomass use

Due to the flows of biomass use along the global supply chain as presented in Section 3, regions in world may take different roles in international trade in terms of biomass use. Figure 12 shows the intermediate and final trade imbalance in terms of biomass use for each region. The size of the sphere represents the total trade volume of biomass use for each region. The most prominent consumer, the United States, is situated in the first quadrant, alongside other developed countries like the United Kingdom, Japan, France, and Germany. It is noticeable that some European countries, such as the United Kingdom, Germany, and France, are outstanding in the interregional trade of biomass use. As illustrated in previous sections, Brazil, the United States, China, and India are the major contributors to the inflows of biomass use into European countries. For Brazil, India, Cyprus, and Indonesia, they are situated in the third quadrant. They are net exporters of biomass use in both intermediate and final trade. Also, biomass exploitation mainly occurs in these regions. While for Canada, it is located in the second quadrant, obtaining a deficit of biomass use in intermediate trade but a surplus in final trade. It implies that Canada exports a considerable quantity of products for intermediate production and also imports biomass-intensive products for final consumption at the same time. In contrast to Canada, Mainland China, and South Korea get a trade surplus of biomass use in intermediate trade but a deficit in final trade (though a small amount).

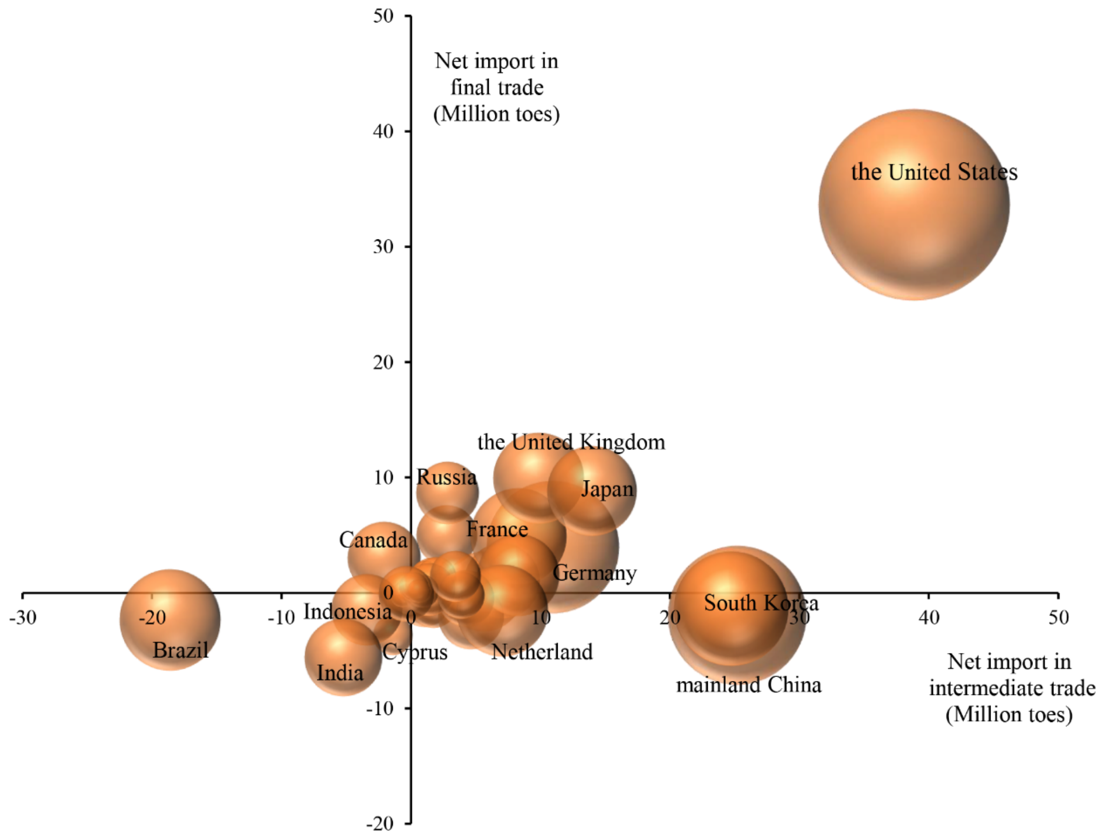


Figure 12. Trade imbalance in terms of biomass use

The trade imbalance in terms of biomass use is compared with the monetary trade imbalance for each region. As shown in Figure 13, the United States is prominent in the second quadrant because of its high level of trade surplus of biomass use and negative economic trade balance. Though the United States' economic trade deficit is up to 480.58 billion dollars, it imports 72.48 million toe of biomass use in an invisible way. For a long time, the United States is faced with a vast economic trade deficit and has adopted many protection-oriented policies to settle it. Though the exports of high value-added products have alleviated the trade deficit caused by the biomass use imports to some extent, the fact that its economy is highly consumption-oriented has not changed. The United Kingdom, France, and Japan are in accordance with the United States in that they are net importers in terms of biomass use and receive a deficit in terms of currency. Mainland China, Germany, and South Korea, like other prominent economies, lie in the first quadrant. Mainland China's economic trade surplus (582.63 billion dollars) exceeds that of the United States. The situation of Germany and South Korea is similar to that of China. They are net importers in terms of biomass use and also gain a monetary surplus in trade. Inversely, Brazil and India are two prominent countries in the third quadrant. They depend heavily on exporting biomass-intensive products to foreign regions and also has a deficit of currency. Brazil's economic and embodied biomass trade deficits are respectively 47.08 billion dollars and 20.95 million toe, revealing a severe situation for Brazil's sustainable development.

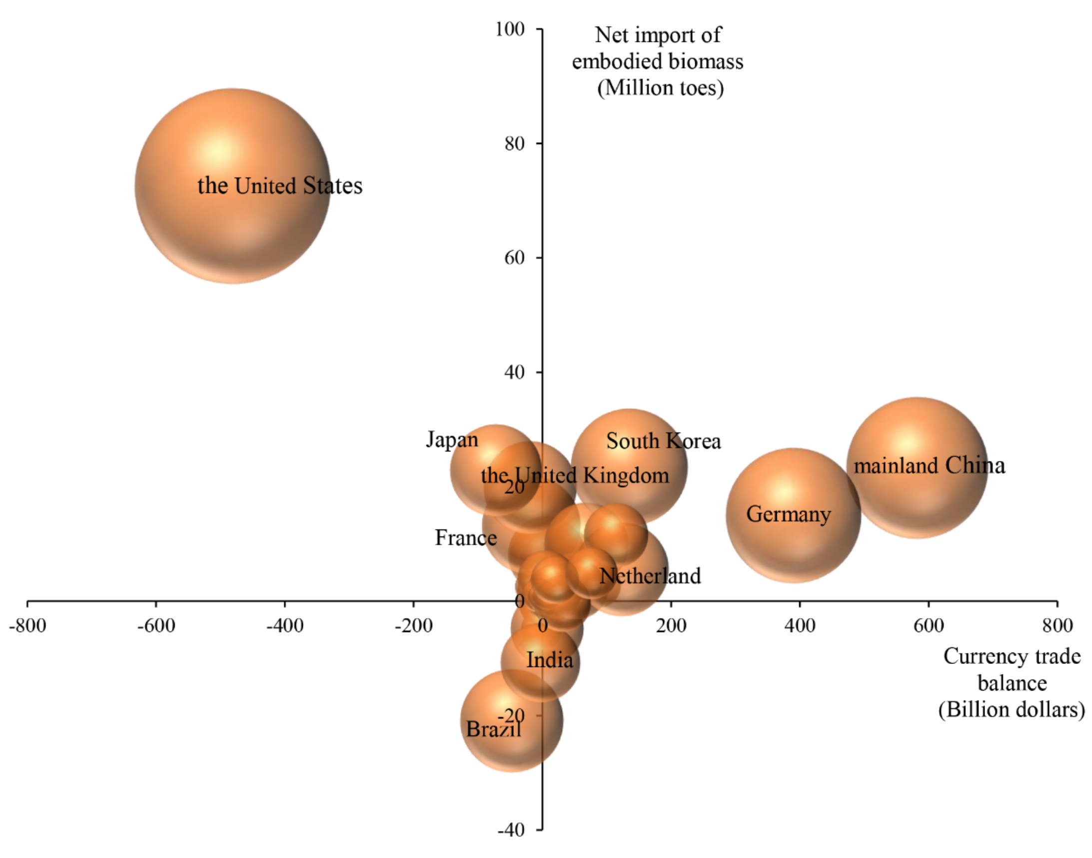


Figure 13. Trade imbalance in terms of biomass use and currency use

4.2. Shift of the associated environmental welfare between world regions along the global supply chain

As could be seen from the results, the United States, Germany, Japan, and China are the major net importers of biomass use. These economies enjoy environmental welfare and avoid the potential environmental impact when they invisibly consume foreign biomass resources. Endowed with limited biomass resources, countries like Japan, South Korea, Denmark, Switzerland, and the United Kingdom, resort to imports from foreign countries to meet their domestic demand for biomass use. With a comparatively high level of economic development, they mainly import primary agricultural products to improve the living standards of local residents, while exporting a considerable quantity of high value-added products that are much less biomass-intensive. As a result, immense biomass use is induced in foreign regions to meet its final demand. While it can help bring economic benefits to those regions, it also increases the severity of the resource depletion and environmental crisis in those regions.

Trade structure, which is closely related to the industrial structure, affects the roles of regions in the global supply chain. Brazil, India, Cyprus, and Indonesia are regions with long agricultural traditions, and they have natural advantages in exporting biomass-intensive products, mainly primary products, to meet the demands of other countries in both industrial manufacturing and final consumption. Take Brazil for example, *Agriculture and animal husbandry* serves as the pillar industry, which is accountable for around one-third of the gross domestic products. There is about 17.7 million rural labor force involved in the agricultural industry, accounting for 37% of the total employment in Brazil. Therefore, the agricultural exports occupy a very large proportion of the total exports, and *Agriculture* industry is seen as a locomotive to the Brazilian economy. Generally, Brazil relies heavily on exporting agricultural goods to mainland China and European countries to back their intermediate production. As an economy with robust manufacturing industries, China has received a remarkable amount of biomass use in intermediate trade by importing biomass-intensive products from other regions as intermediate inputs for further processing. The biomass use inflows of China are mainly from Brazil and the United States, who are also big contributors to EU28's imported biomass use. The United States is also active in interregional trades, whose biomass use embodied in imports is nearly equal to the local biomass exploitation. Though the United States has a rich endowment of biomass resources due to its natural geographical conditions, it gains benefits by exporting high value-added products and importing biomass-intensive goods that are mostly low value-added. Therefore, the trade structure in developed countries is oriented towards economic blossom, environmental protection, and sustainable development. It is worth noting that developed countries have paid much attention to sustainable development. Taking the United States, for instance, it has provided substantial subsidies and technological investment for biomass deployment in order to safeguard energy security and low-carbon development. For instance, the Biomass Crop Assistance Program (*BCAP*) was re-approved in the Farm Bill in 2004 and implemented in the same year, with 25 million dollars authorized annually as the supporting funds. The enormous financial and technological investments have made the United States a major consumer and producer of biomass use. However, the United States, as a consumption-oriented nation, still imports a large quantity of biomass use via the global supply chain to satisfy its high-level consumptive demands and mitigate the concerns of biomass resource depletion as well as the related environmental stress at the same time.

Brazil and India are two major exporters of biomass-intensive goods that shift the associated environmental welfare to foreign regions. Meanwhile, the environmental impacts induced by biomass demand and produced in biomass exploitation and production are kept at home. Nevertheless, insufficient attention has been paid to achieving the sustainable use of these natural assets in these nations. For instance, Brazil is highlighted as the global biomass market due to its mass production of plantation crops such as sugarcane. The Brazilian government has provided preferential policies and financial subsidies to the farmers, stimulating their plantation activities to increase income and also using these supportive incentives as important strategies for economic development. Negative effects in biomass exploitation, such as water pollution, soil erosion, and loss of biodiversity, are therefore induced in these export-oriented countries (most of whom are developing nations). Generally, though biomass-intensive products are generally acknowledged as clean and sustainable from the consumer side, the environmental impacts induced in the exploitation process and other stages (such as feedstock production) along the global supply chain are generally overlooked [11]. Existing studies have reported that biomass exploitation and production would impose grave stress on the water, soil, air, biodiversity, and ecosystem service, as summarized in Table 1. This is particularly serious in developing countries with primitive technology and poor economic conditions. Due to the neglect of environmental costs incurred during the exploitation of natural resources, the economic revenues generated from exports of resource-intensive products might be largely jeopardized, not to mention the large quantity of monetary inputs that regions have to invest for environmental restoration.

Table 1. A review of environmental impacts of biomass production

Water	Nutrient pollution	[44-48]
	Hypoxia	[46,49-51]
	Pesticide runoff	[52-55]
	Shortage	[56,57]
	Life cycle assessment	[58,59]
Soil	Degradation	[60,61]
	Organic reduction	[62-65]
Air	Life-cycle greenhouse gas emissions (CO, NO_X, VOC, PM_X, SO_X)	[45,64,66-69]
Biodiversity	Mono-culture and habitat stress	[70-77]
	Invasion species	[78-81]
Ecosystem service[①]	Provision degradation（food, fresh water, wood et al.）	[82-87]
	Regulation degradation（climate, flood disease, water regulation et al.）	
	Recreation decline	
	Support degradation (soil formation, nutrient cycling et al.)	

Note: ①Categories of ecosystem service are mainly referred to Millennium Ecosystem Assessment.

Based on a review of a significant body of literature, it could be concluded that in most cases, the environmental benefit of biomass utilization is only reflected on the consumer side, while its exploitation process and other production stages are not as environmental-friendly as expected. The regions serving as the primary source bear the environmental impacts induced by biomass exploitation. On the other hand, regions serving as the sink of final consumption enjoy the associated environmental welfare and also invisibly mitigate the ecological concerns, which may lead to the situation of regional decrease but a global increase from an embodiment perspective.

5. Concluding remarks

5.1. Conclusions

Globalization leads to the interregional transfer of biomass use via the global supply chain. An overview of biomass use for the world economy is presented in this study based on the WIOD database in 2014. We track the dynamic process of global biomass resources from primary exploitation to final consumption. Besides, the roles of the nations in the global supply chains are identified via a source-to-sink manner. The outcome shows that through the channels of the global supply chain, the shift of environmental welfare from biomass-exporting nations to biomass-importing nations occurs along with interregional trade.

In addition to the work that has already done in this paper, there is still much room for further improvement. First, it is imperative to conduct a time-series analysis, which can track the temporal process and evolution of biomass use in the global value chain. Second, due to the sectoral classification of WIOD, *Agriculture* is a broad sector without more detailed division, it will affect the assignment of the exploited biomass with corresponding sectors. Therefore, a more elaborate division of sectors will contribute to the optimization of the research. Third, further studies could be also conducted to compared the results derived under different multi-region input-output databases, which may demonstrate the impact of statistical economic data on the accuracy of the results.

5.2. Policy implications

This study has discussed the associated environmental welfare shift from the source regions to those consumption-oriented economies known as sinks via interregional trade is observed. Some recommendations are presented below on sustainable exploitation and reasonable use of biomass resource.

For the biomass source regions such as Brazil and India, we suggest that they should strike a balance between economic revenues and long-term sustainability. Generally speaking, these source regions are heavily dependent on selling a colossal amount of primary biomass products to the international market for economic revenues, products ending up sunk into the consumption-oriented nations, and such excessive reliance upon exporting resource-intensive product is not healthy for these regions' long-term sustainable development of these source regions. Therefore, source regions should take rational and comprehensive consideration on the ecological cost of biomass development when devising energy strategies, and, in order to achieve long-term sustainability in addition to improving both the economic and ecological efficiency of biomass exploitation and production, it is imperative for these regions to undergo a transition of trading structure from resource-oriented to high-tech- and service-oriented structure.

As for the consumption-oriented nations serving as the sink of biomass use (such as the United States and Japan.), an increase in the energy efficiency of high value-added industries, such as financial services, insurance, and public administrate, is recommended. Although these service sectors do not directly consume the biomass resources, they are powerful pumps driving the interregional biomass flows, inducing mass biomass resource exploitation in upstream processes. Meanwhile, the consumption-oriented countries that enjoy the environmental benefits are also recommended to provide various compensation to offset the environmental impact induced by their consumption. Taxation or decent price, for example, should reconcile the ecological unequal exchanges. In addition, the consumption-oriented countries should also provide certain technical and economic support to corresponding exporting countries. Supporting incentives such as clean development mechanism and belt-road initiative may serve as a superb example of technology transfer, which can improve the infrastructure and enhance the source regions' industrial production efficiency of biomass exploitation.

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References

[1] Scarlat, N., Dallemand, J.F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development. 15, 3-34. https://doi.org/10.1016/j.envdev.2015.03.006

[2] Wasiak, A.L., 2017. Effect of biofuel production on sustainability of agriculture. Procedia Engineering. 182, 739-746. https://doi.org/10.1016/j.proeng.2017.03.192

[3] Welfle, A., 2017. Balancing growing global bioenergy resource demands: Brazil's biomass potential and the availability of resource for trade. Biomass and Bioenergy. 105, 83-95. https://doi.org/10.1016/j.biombioe.2017.06.011

[4] Alemán-Nava, G.S., Casiano-Flores, V.H., Cárdenas-Chávez, D.L., Díaz-Chavez, R., Scarlat, N., Mahlknecht, J., Dallemand, J.F., Parra, R., 2014. Renewable energy research progress in Mexico: A review. Renewable and Sustainable Energy Reviews. 32, 140-153. https://doi.org/10.1016/j.rser.2014.01.004

[5] Joshi, G., Pandey, J.K., Rana, S., Rawat, D.S., 2017. Challenges and opportunities for the application of biofuel. Renewable and Sustainable Energy Reviews 79, 850-866. https://doi.org/10.1016/j.rser.2017.05.185

[6] Haykiri-Acma, H., Yaman, S., 2010. Interaction between biomass and different rank coals during co-pyrolysis. Renewable Energy. 35, 288-292. https://doi.org/10.1016/j.renene.2009.08.001

[7] BP, 2018. BP Statistical Review of World Energy 2017. Technical Report.

[8] Heinimö, J., 2008. Methodological aspects on international biofuels trade: International streams and trade of solid and liquid biofuels in Finland. Biomass and Bioenergy. 32, 702-716. https://doi.org/10.1016/j.biombioe.2008.01.003

[9] Kaditi, E.A., 2009. Bio-energy policies in a global context. Journal of Cleaner Production. 17, S4-S8. https://doi.org/10.1016/j.jclepro.2008.08.023

[10] Matzenberger, J., Kranzl, L., Tromborg, E., Junginger, M., Daioglou, V., Goh, C.S., Keramidas, K., 2015. Future perspectives of international bioenergy trade. Renewable and Sustainable Energy Reviews. 43, 926-941. https://doi.org/10.1016/j.rser.2014.10.106

[11] Ji, X., Long, X.L., 2016. A review of the ecological and socioeconomic effects of biofuel and energy policy recommendations. Renewable and Sustainable Energy Reviews. 61, 41-52. https://doi.org/10.1016/j.rser.2016.03.026

[12] Junginger, M., Bolkesjø, T., Bradley, D., Dolzan, P., Faaij, A., Heinimö, J., Hektor, B., Leistad, Ø., Ling, E., Perry, M., Piacente, E., Rosillo-Calle, F., Ryckmans, Y., Schouwenberg, P.-P., Solberg, B., Trømborg, E., Walter, A. da S., Wit, M. de, 2008. Developments in international bioenergy trade. Biomass and Bioenergy. 32, 717-729. https://doi.org/10.1016/j.biombioe.2008.01.019

[13] Demirbas, A., 2009. Political, economic and environmental impacts of biofuels: A review. Applied Energy. 86, S108-S117. https://doi.org/10.1016/j.apenergy.2009.04.036

[14] Chen, G.Q., Wu, X.F., 2017. Energy overview for globalized world economy: Source, supply chain and sink. Renewable and Sustainable Energy Reviews. 69, 735-749. https://doi.org/10.1016/j.rser.2016.11.151

[15] Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.M., Liu, Z., Hubacek, K., 2017. Chinese CO_2 emission flows have reversed since the global financial crisis. Nature Communications. 8(1), 1712. https://doi.org/10.1038/s41467-017-01820-w

[16] Meng, J., Zhang, Z.K., Mi, Z., Anadon, L.D., Zheng, H., Zhang, B., Shan, Y.L., Guan, D.B., 2018a. The role of intermediate trade in the change of carbon flows within China. Energy Economics. 76, 303-312. https://doi.org/10.1016/j.eneco.2018.10.009

[17] Lin, J., Du, M., Chen, L., Liu, Y., Feng, K., Martin, R., Wang, J., Ni, R., Zhao, Y., Kong, H., Weng, H., Liu, M., van Donkelaar, A., Liu, Q., Hubacek, K., 2019. Carbon and health implications of trade restrictions. Nature Communications. 10: 4947 .

[18] Zhang, Z., Zhu, K., Hewings, G.J.D., 2017. A multi-regional input-output analysis of the pollution haven hypothesis from the perspective of global production fragmentation. Energy Economics. 64, 13-23. https://doi.org/10.1016/j.eneco.2017.03.007

[19] Zhang, Z., Lin, J., 2018. From production-based to consumption-based regional carbon inventories: Insight from spatial production fragmentation. Applied Energy. 211, 549-567. https://doi.org/10.1016/j.apenergy.2017.11.047

[20] Wang, H., Ang, B.W., 2018. Assessing the role of international trade in global CO2 emissions: An index decomposition analysis approach. Applied Energy. 218, 146-158. https://doi.org/10.1016/j.apenergy.2018.02.180

[21] Johnson, R.C., Noguera, G., 2012. Fragmentation and trade in value added over four decades. National Bureau of Economic Research, Inc.

[22] Chen, G.Q., Wu, X.D., Guo, J., Meng, J., Li, C., 2019. Global overview for energy use of the world economy: Household-consumption-based accounting based on the world input-output database (WIOD). Energy Economics 81, 835-847. https://doi.org/10.1016/j.eneco.2019.05.019

[23] Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: A global, trade-linked analysis. Environment Science and Technology. 43, 6414-6420. https://doi.org/10.1021/es803496a

[24] Chen, G., Wiedmann, T., Wang, Y., Hadjikakou, M., 2016. Transnational city carbon footprint networks: Exploring carbon links between Australian and Chinese cities. Applied Energy. 184, 1082-1092. https://doi.org/10.1016/j.apenergy.2016.08.053

[25] Su, B., Ang, B.W., 2011. Multi-region input-output analysis of CO_2 emissions embodied in trade: The feedback effects. Ecological Economics. 71(15), 42-53. https://doi.org/10.1016/j.ecolecon.2011.08.024

[26] Meng, J., Mi, Z., Guan, D., Li, J., Tao, S., Li, Y., Feng, K., Liu, J., Liu, Z., Wang, X., Zhang, Q., Davis, S.J., 2018b. The rise of South-South trade and its effect on global CO_2 emissions. Nature Communications. 9 (1), 1871. https://doi.org/10.1038/s41467-018-04337-y

[27] Ji, X., Liu, Y., Han, M., Meng, J., 2020. The mutual benefits from Sino-Africa trade: Evidence on emission transfer along the global supply chain. Journal of Environmental Management. 263, 110332. https://doi.org/10.1016/j.jenvman.2020.110332

[28] Camaratta, R., Volkmer, T.M., Osorio, A.G., 2020. Embodied energy in beverage packaging. Journal of Environmental Management. 260, 110172. https://doi.org/10.1016/j.jenvman.2020.110172

[29] Chen, B., Li, J.S., Wu, X.F., Han, M.Y., Zeng, L., Li, Z., Chen, G.Q., 2018. Global energy flows embodied in international trade: A combination of environmentally extended input–output analysis and complex network analysis. Applied Energy, 210, 98-107. https://doi.org/10.1016/j.apenergy.2017.10.113

[30] Ji, X., Han, M., Ulgiati, S., 2020. Optimal allocation of direct and embodied arable land associated to urban economy: Understanding the options deriving from economic globalization. Land Use Policy. 91, 104392. https://doi.org/10.1016/j.landusepol.2019.104392

[31] Feng, K., Chapagain, A., Suh, S., Pfister, S., Hubacek, K., 2011. Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. Economic Systems Research. 23, 371-385. https://doi.org/10.1080/09535314.2011.638276

[32] Wu, X.F., Chen, G.Q., 2019. Global overview of crude oil use: From source to sink through inter-regional trade. Energy Policy. 128, 476-486. https://doi.org/10.1016/j.enpol.2019.01.022

[33] Wu, X.F., Chen, G.Q., 2018. Coal use embodied in globalized world economy: From source to sink through supply chain. Renewable and Sustainable Energy Reviews. 81, 978-993. https://doi.org/10.1016/j.rser.2017.08.018

[34] Kan, S.Y., Chen, B., Wu, X.F., Chen, Z.M., Chen, G.Q., 2019a. Natural gas overview for world economy: From primary supply to final demand via global supply chains. Energy Policy. 124, 215-225. https://doi.org/10.1016/j.enpol.2018.10.002

[35] Kohlheb, N., Krausmann, F., 2009. Land use change, biomass production and HANPP: The case of Hungary 1961-2005. Ecological Economics, Special Section: Analyzing the global human appropriation of net primary production - processes, trajectories, implications. 69, 292-300. https://doi.org/10.1016/j.ecolecon.2009.07.010

[36] Ma, T., Zhou, C., Pei, T., 2012. Simulating and estimating tempo-spatial patterns in global human appropriation of net primary production (HANPP): A consumption-based approach. Ecological Indicators. 23, 660-667. https://doi.org/10.1016/j.ecolind.2012.05.026

[37] Haberl, H., Kastner, T., Schaffartzik, A., Ludwiczek, N., Erb, K.-H., 2012. Global effects of national biomass production and consumption: Austria's embodied HANPP related to agricultural biomass in the year 2000. Ecological Economics. 84, 66-73. https://doi.org/10.1016/j.ecolecon.2012.09.014

[38] Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009. Embodied HANPP: Mapping the spatial disconnect between global biomass production and consumption. Ecological Economics, Special Section: Analyzing the global human appropriation of net primary production - processes, trajectories, implications. 69, 328-334. https://doi.org/10.1016/j.ecolecon.2009.06.025

[39] Saikku, L., Mattila, T.J., 2017. Drivers of land use efficiency and trade embodied biomass use of Finland 2000-2010. Ecological Indicators. 77, 348-356. https://doi.org/10.1016/j.ecolind.2017.02.021

[40] Smith, A., 1776. An inquiry into the nature and causes of the wealth of nations. W.Strahan and T. Cadell, London.

[41] Kan, S., Chen, B., Chen, G., 2019b. Worldwide energy use across global supply chains: Decoupled from economic growth? Applied Energy. 250, 1235-1245. https://doi.org/10.1016/j.apenergy.2019.05.104

[42] Wu, X.D., Guo, J.L., Han, M.Y., Chen, G.Q., 2018. An overview of arable land use for the world economy: From source to sink via the global supply chain. Land Use Policy. 76, 201-214. https://doi.org/10.1016/j.landusepol.2018.05.005

[43] Wu, X.D., Guo, J.L., Li, C.H., Shao, L., Han, M.Y., Chen, G.Q., 2019. Global socio-hydrology: An overview of virtual water use by the world economy from source of exploitation to sink of final consumption. Journal of Hydrology. 573, 794-810. https://doi.org/10.1016/j.jhydrol.2019.03.080

[44] Simpson, T.W., Sharpley, A.N., Howarth, R.W., Paerl, H.W., Mankin, K.R., 2008. The new gold rush: Fueling ethanol production while protecting water quality. Journal of Environmental Quality. 37, 318-324. https://doi.org/10.2134/jeq2007.0599

[45] EPA, 2011. Biofuels and the environment: first triennial report to congress. Report no. EPA/600/R-10/183F. National Center for Environmental Assessment.

[46] Wu, Y.P., Liu, S.G., Li, Z.P., 2012. Identifying potential areas for biofuel production and evaluating the environmental effects: A case study of the James River basin in the Midwestern United States. Global Change Biology Bioenergy. 4, 875-888. https://doi.org/10.1111/j.1757-1707.2012.01164.x

[47] Mubako, S., Lant, C., 2008. Water resource requirements of corn-based ethanol. Water Resource Research. 44,134-143. https://doi.org/10.1029/2007WR006683

[48] King, C.W., Stillwell, A.S., Twomey, K.M., Webber, M.E., 2013. Coherence between water and energy policies. Natural Resource Journal. 53, 117-215.

[49] EPA, 2007. Hypoxia in the Northerm Gulf of Mexico. Report no. EPA-SAB-08-003.

[50] Costello, C., Griffin, W. M., Landis, A.E., Matthews, H.S., 2009. Impact of biofuel crop production on the formation of hypoxia in the Gulf of Mexico. Environmental Science & Technology. 43, 7985-7991. https://doi.org/10.1021/es9011433

[51] Hendricks, N.P., Sinnathamby, S., Douglas-Mankin, K., Smith, A., Sumner, D.A., Earnhart, D.H., 2014. The environmental effects of crop price increases: Nitrogen

losses in the US corn belt. Journal of Environmental Economic Management. 68, 507-526. https://doi.org/ 10.1016/j.jeem.2014.09.002

[52] Spalding, R., Exner, M.E., 1993. Occurrence of nitrate in groundwater: A review. Journal of Environmental Quality. 22, 392-402. https://doi.org/10.2134/jeq1993.00472425002200030002x

[53] DeSimone, L.A., 2009. Quality of water from domestic wells in principal aquifers of the United States, 1991-2004. Report no. 2008-5227. USGS, National Water Quality Assessment Program.

[54] Stone, W.W., Gilliom, R.J., Ryberg, K.R., 2014. Pesticides in U.S. streams and rivers: Occurrence and trends during 1992-2011. Environmental Science & Technology. 48, 11025-11030. https://doi.org/ 10.1021/es5025367

[55] Nordborg, M., Cederberg, C., Berndes, G., 2014. Modeling potential freshwater ecotoxicity impacts due to pesticide use in biofuel feedstock production: The cases of maize, rapeseed, salix, soybean, sugar cane, and wheat. Environmental Science & Technology. 48, 11379-11388. https://doi.org/10.1021/es502497p

[56] Wu, M., Mintz, M., Wang, M., Arora, S., 2009. Water consumption in the production of ethanol and petroleum gasoline. Environmental Management. 44, 981-997. https://doi.org/ 10.1007/s00267-009-9370-0

[57] Dominguez-Faus, R., Powers, S.E., Burken, J.G., Alvarez, P.J., 2009. The water footprint of biofuels: A drink or drive issue? Environmental Science & Technology. 43, 3005-3010. https://doi.org/10.1021/es802162x

[58] Yang, Q., Liang, J., Li, J., Yang, H., Chen, H., 2018a. Life cycle water use of a biomass-based pyrolysis polygeneration system in China. Applied Energy. 224, 469-480. https://doi.org/10.1016/j.apenergy.2018.05.009

[59] Zhu, Y., Liang, J., Yang, Q., Zhou, H., Peng, K., 2019. Water use of a biomass direct-combustion power generation system in China: A combination of life cycle assessment and water footprint analysis. Renewable and Sustainable Energy Reviews. 115, 109396. https://doi.org/10.1016/j.rser.2019.109396

[60] Pimentel, D., 2006. Soil erosion: A food and environmental threat. Environment Development & Sustainability. 8, 119-137. https://doi.org/10.1007/s10668-005-1262-
[61] Pimentel, D., Patzek, T. W., Cecil, G., 2007. Ethanol production: energy, economic, and environmental losses. Reviews of Environmental Contamination Toxicology. 189, 25-41. https://doi.org/10.1007/978-0-387-35368-5_2
[62] Burke, I.C., Yonker, C.M., Parton, W.J., Cole, C.V., Schimel, D.S., Flach, K., 1989. Texture, climate, and cultivation effects on soil organic-matter content in US grassland soils. Soil Science Society of America Journal. 53, 800-805. https://doi.org/10.2136/sssaj1989.03615995005300030029x
[63] Drewniak, B.A., Mishra, U., Song, J., Prell, J., Kotamarhi, V.R., 2015. Modeling the impact of agricultural land use and management on US carbon budgets. Biogeosciences. 12, 2119-2129. https://doi.org/10.5194/bg-12-2119-2015
[64] Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F.X., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.H., 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science. 319, 1238-1240. https://doi.org/10.1126/science.1151861
[65] Liska, A.J., Yang, H.S., Milner, M., Goddard, S., Blanco-Canqui, H., Pelton, M.P., Fang, X.X., Zhu, H.T., Suyker, A.E., 2014. Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. Nature Climate Change. 4, 398-401. https://doi.org/10.1038/NCLIMATE2187
[66] Hess, P., Johnston, M., Brown-Steiner, B., Holloway, T., de Andrade, J.B., Artaxo, P., 2009. Chapter 10: Air quality issues associated with biofuel production and use. In: Howarth, R.W., Bringezu, S., editors. Biofuels: Environmental consequences and interactions with changing land use. Gummersbach, Germany.
[67] Xue, J.L., Grift, T.E., Hansen, A.C., 2011. Effect of biodiesel on engine performances and emissions. Renewable and Sustainable Energy Reviews. 15, 1098-1116. https://doi.org/10.1016/j.rser.2010.11.016
[68] Yang, Q., Chen, G.Q., 2013. Greenhouse gas emissions of corn-ethanol production in China. Ecological Modelling, Ecological Modelling for Global Change and

Coupled Human and Natural Systems. 252, 176-184. https://doi.org/10.1016/j.ecolmodel.2012.07.011

[69] Yang, Q., Zhou, H., Zhang, X., Nielsen, C.P., Li, J., Lu, X., Yanga, H., Chen, H., 2018b. Hybrid life-cycle assessment for energy consumption and greenhouse gas emissions of a typical biomass gasification power plant in China. Journal of Cleaner Production. 205, 661-671. https://doi.org/10.1016/j.jclepro.2018.09.041

[70] Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E.L., Bloomfield, J.B., Dirzo, R.H., Huber-Sanwald, E., Huenneke, L., Jackson, R.B., Kinzig, A.P., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B., Walker, M., Wall, D.H., 2000. Biodiversity-Global biodiversity scenarios for the year 2100. Science. 287, 1770-1774. https://doi.org/10.1126/science.287.5459.1770

[71] Brady, S.J., 2007. Effects of cropland conservation practices on fish and wildlife habitat. In: Haufler JB, editor. Fish and Wildlife Response to Farm Bill Conservation Practices. The Wildlife Society.

[72] Fargione, J.E., 2010. Is bioenergy for the birds? An evaluation of alternative future bioenergy landscapes. Proceedings of the National Academy of Sciences. 107, 18745-18746. https://doi.org/ 10.1073/pnas.1014045107

[73] Robertson, B.A., Doran, P.J., Loomis, L. R., Robertson, J. R., Schemske, D.W., 2011. Perennial biomass feedstocks enhance avian diversity. Global Change Biology Bioenergy. 3, 235-246. https://doi.org/10.1111/j.1757-1707.2010.01080.x

[74] Struebig, M., Kingston, T., Petit, E., Comber, S.L., Zubaid, A., Mohd-Adnan, A., Rossiter, S., 2011. Parallel declines in species and genetic diversity in tropical forest fragments. Ecology Letters. 16, 582-590. https://doi.org/10.1111/j.1461-0248.2011.01623.x

[75] Uden, D., Allen, C.R., Mitchell, R., McCoy, T.D., Guan, Q.F., 2015. Predicted avian responses to bioenergy development scenarios in an intensive agricultural landscape. Global Change Biology Bioenergy. 7, 717-726. https://doi.org/10.1111/gcbb.12157

[76] Joly, C.A., Verdade, L.M., Huntley, B.J., Dale, V.H., Mace, G., Muok, B., Ravindranath, N.H., 2015. Biofuel impacts on biodiversity and ecosystem services.

Scientific Committee on Problems of the Environment (SCOPE) Rapid Assessment Process on Bioenergy and Sustainability.

[77] DeGennaro, D., 2016. Fueling destruction: The unintended consequences of the renewable fuel standard on land, water, and wildlife. Washington, DC: National Wildlife Foundation.

[78] Barney, J.N., DiTomaso, J.M., 2008. Nonnative species and bioenergy: Are we cultivating the next invader? BioScience. 5, 64-70. https://doi.org/10.1641/B580111

[79] Barney, J.N., DiTomaso, J.M., 2010. Invasive species biology, ecology, management and risk assessment: Evaluating and mitigating the invasion risk of biofuel crops. In: Mascia, P.N., editor. Plant Biotechnology for Sustainable Production of Energy and Co-Products. Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-642-13440-1_9

[80] Barney, J.N., DiTomaso, J.M., 2011. Global climate niche estimates for bioenergy crops and invasive species of agronomic origin: potential problems and opportunities. Plos One. 6, 1-11. https://doi.org/ 10.1371/journal.pone.0017222

[81] Lewis, K.C., Porter, R.D., 2014. Global approaches to addressing biofuel-related invasive species risks and incorporation into US laws and policies. Ecological Monographs. 84, 171-201. https://doi.org/10.1890/13-1625.1

[82] Fargione, J.E., Hill J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science. 319, 1235-1237. https://doi.org/10.1126/science.1152747

[83] Fargione, J.E., Cooper, T.R., Flaspohler, D.J., Hill, J., Lehman, C., McCoy, T., McLeod, S., Nelson, E.J., Oberhauser, K.S., Tilman, D., 2009. Bioenergy and wildlife: Threats and opportunities for grassland conservation. BioScience. 59, 767-777. https://doi.org/10.1525/bio.2009.59.9.8

[84] Secchi, S., Kurkalova, L., Gassman, P.W., Hart, C., 2011. Land use change in a biofuels hotspot: The case of Iowa, USA. Biomass & Bioenergy. 35, 2391-2400. https://doi.org/10.1016/j.biombioe.2010.08.047

[85] Wright, C.K., Wimberly, M.C., 2013. Recent land use change in the western corn belt threatens grasslands and wetlands. Proceedings of the National Academy of Sciences of the United States of USA. 110, 4134-4139. https://doi.org/10.1073/pnas.1215404110

[86] Holma, A., Koponen, K., Antikainen, R., Lardon, L., Leskinen, P., Roux, P., 2013. Current limits of life cycle assessment framework in evaluating environmental sustainability: Case of two evolving biofuel technologies. Journal of Cleaner Production. 54, 215-228. https://doi.org/10.1016/j.jclepro.2013.04.032

[87] Liu, Y., Xu, Y., Zhang, F.C., Yun, J.Q., Shen, Z.H., 2014. The impact of biofuel plantation on biodiversity: A review. Chinese Science Bulletin. 59, 4639-4651. https://doi.org/10.1007/s11434-014-0639-1

Appendixes

Appendix A

Regions included in the world economic input-output table

Code	Region	Code	Region
1	Australia	23	Ireland
2	Austria	24	Italy
3	Belgium	25	Japan
4	Bulgaria	26	South Korea
5	Brazil	27	Lithuania
6	Canada	28	Luxembourg
7	Switzerland	29	Latvia
8	mainland China	30	Mexico
9	Cyprus	31	Malta
10	Czech Republic	32	Netherlands
11	Germany	33	Norway
12	Denmark	34	Poland
13	Spain	35	Portugal
14	Estonia	36	Romania
15	Finland	37	Russia
16	France	38	Slovakia
17	the United Kingdom	39	Slovenia
18	Greece	40	Sweden
19	Croatia	41	Turkey
20	Hungary	42	Taiwan
21	Indonesia	43	the United States
22	India	44	ROW

Appendix B

Sectors included in the world economic input-output table

Sector code	**Sector content**	**Sector code**	**Sector content**
1	Crop and animal production, hunting and related service activities	29	Wholesale trade, except of motor vehicles and motorcycles
2	Forestry and logging	30	Retail trade, except of motor vehicles and motorcycles
3	Fishing and aquaculture	31	Land transport and transport via pipelines
4	Mining and quarrying	32	Water transport
5	Manufacture of food products, beverages and tobacco products	33	Air transport
6	Manufacture of textiles, wearing apparel and leather products	34	Warehousing and support activities for transportation
7	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	35	Postal and courier activities
8	Manufacture of paper and paper products	36	Accommodation and food service activities
9	Printing and reproduction of recorded media	37	Publishing activities
10	Manufacture of coke and refined petroleum products	38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
11	Manufacture of chemicals and chemical products	39	Telecommunications
12	Manufacture of basic pharmaceutical products and pharmaceutical preparations	40	Computer programming, consultancy and related activities; information service activities
13	Manufacture of rubber and plastic products	41	Financial service activities, except insurance and pension funding
14	Manufacture of fabricated metal products, except machinery and equipment	42	Insurance, reinsurance and pension funding, except compulsory social security
15	Manufacture of computer, electronic and optical products	43	Activities auxiliary to financial services and insurance activities

16	Manufacture of electrical equipment	44	Real estate activities
17	Manufacture of machinery and equipment n.e.c.	45	Legal and accounting activities; activities of head offices; management consultancy activities
18	Manufacture of motor vehicles, trailers and semi-trailers	46	Architectural and engineering activities; technical testing and analysis
19	Manufacture of other transport equipment	47	Scientific research and development
20	Manufacture of furniture; other manufacturing	48	Advertising and market research
21	Repair and installation of machinery and equipment	49	Other professional, scientific and technical activities; veterinary activities
22	Electricity, gas, steam and air conditioning supply	50	Administrative and support service activities
23	Water collection, treatment and supply	51	Public administration and defence; compulsory social security
24	Construction	52	Education
25	Wholesale and retail trade and repair of motor vehicles and motorcycles	53	Human health and social work activities
26	Wholesale trade, except of motor vehicles and motorcycles	54	Other service activities
27	Retail trade, except of motor vehicles and motorcycles	55	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
28	Land transport and transport via pipelines	56	Activities of extraterritorial organizations and bodies

Appendix C

Embodied biomass in final consumption and trades

Region	*EEC*	*Per capita EEC*	*ERD*	*EEI*	*EEX*	*EEB*
Australia	10.76	0.46	5.10	10.54	2.79	7.75
Austria	5.46	0.64	5.77	5.42	5.00	0.42
Belgium	7.04	0.63	2.93	14.37	8.64	5.73
Bulgaria	1.05	0.15	1.19	0.74	0.77	-0.04
Brazil	57.13	0.28	84.30	7.88	28.83	-20.95
Canada	13.71	0.39	14.00	10.05	9.11	0.94
Switzerland	4.31	0.53	2.35	4.91	2.16	2.75
mainland China	103.30	0.08	114.00	46.19	22.94	23.26
Cyprus	24.09	20.91	27.00	0.34	5.40	-5.06
Czech Republic	3.54	0.34	4.04	2.69	2.92	-0.22
Germany	39.63	0.49	29.80	38.95	24.02	14.92
Denmark	2.69	0.48	2.30	4.78	3.96	0.82
Spain	13.69	0.29	7.20	14.25	6.17	8.08
Estonia	0.95	0.72	1.20	0.60	0.68	-0.08
Finland	7.44	1.36	9.10	3.49	4.34	-0.85
France	24.23	0.37	14.50	23.24	10.06	13.18
the United Kingdom	24.33	0.38	7.10	24.76	4.95	19.81
Greece	3.68	0.34	1.12	3.03	0.46	2.57
Croatia	1.54	0.36	1.44	1.00	0.69	0.31
Hungary	2.03	0.21	2.89	1.98	2.49	-0.50
Indonesia	43.03	0.17	58.50	6.72	11.58	-4.86
India	177.56	0.14	193.40	5.48	16.29	-10.81
Ireland	2.40	0.51	0.40	9.02	6.42	2.60
Italy	19.39	0.32	11.10	17.05	7.22	9.83
Japan	30.59	0.24	10.90	25.91	3.10	22.81
South Korea	23.64	0.47	5.60	35.23	11.85	23.38
Lithuania	1.33	0.46	1.28	1.21	1.14	0.06
Luxembourg	0.45	0.82	0.13	1.19	0.79	0.40
Latvia	1.32	0.66	2.20	0.61	1.50	-0.89
Mexico	11.35	0.09	8.70	7.65	3.88	3.78
Malta	0.23	0.53	0.00	0.87	0.59	0.27
Netherlands	8.99	0.53	4.59	17.87	12.36	5.52
Norway	4.24	0.82	1.32	4.53	1.17	3.37
Poland	8.78	0.23	7.68	5.88	4.20	1.68
Portugal	4.02	0.39	3.28	2.47	1.44	1.03
Romania	4.17	0.21	3.84	1.91	1.17	0.74
Russia	17.76	0.12	7.10	12.83	1.35	11.48
Slovakia	1.91	0.35	1.16	1.68	0.85	0.83
Slovenia	1.27	0.62	0.61	1.33	0.60	0.73
Sweden	9.32	0.96	10.84	5.33	5.78	-0.45
Turkey	6.60	0.09	3.49	5.80	2.15	3.65

Taiwan	5.88	0.25	1.66	7.14	2.28	4.86
the United States	159.61	0.50	104.00	102.04	29.55	72.48

Appendix D

Sectoral classification

1	Crop and animal production, hunting and related service activities	Agriculture
2	Forestry and logging	
3	Fishing and aquaculture	
5	Manufacture of food products, beverages and tobacco products	Food
36	Accommodation and food service activities	
4	Mining and quarrying	Manufacturing
6	Manufacture of textiles, wearing apparel and leather products	
7	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	
8	Manufacture of paper and paper products	
9	Printing and reproduction of recorded media	
10	Manufacture of coke and refined petroleum products	
11	Manufacture of chemicals and chemical products	
12	Manufacture of basic pharmaceutical products and pharmaceutical preparations	
13	Manufacture of rubber and plastic products	
14	Manufacture of fabricated metal products, except machinery and equipment	
15	Manufacture of computer, electronic and optical products	
16	Manufacture of electrical equipment	
17	Manufacture of machinery and equipment n.e.c.	
18	Manufacture of motor vehicles, trailers and semi-trailers	
19	Manufacture of other transport equipment	
20	Manufacture of furniture; other manufacturing	
21	Repair and installation of machinery and equipment	
22	Electricity, gas, steam and air conditioning supply	
23	Water collection, treatment and supply	
24	Construction	
25	Wholesale and retail trade and repair of motor vehicles and motorcycles	
26	Wholesale trade, except of motor vehicles and motorcycles	
27	Retail trade, except of motor vehicles and motorcycles	
28	Land transport and transport via pipelines	Service
29	Wholesale trade, except of motor vehicles and motorcycles	
30	Retail trade, except of motor vehicles and motorcycles	
31	Land transport and transport via pipelines	
32	Water transport	
33	Air transport	
34	Warehousing and support activities for transportation	
35	Postal and courier activities	

37	Publishing activities	
38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	
39	Telecommunications	
40	Computer programming, consultancy and related activities; information service activities	
41	Financial service activities, except insurance and pension funding	
42	Insurance, reinsurance and pension funding, except compulsory social security	
43	Activities auxiliary to financial services and insurance activities	
44	Real estate activities	
45	Legal and accounting activities; activities of head offices; management consultancy activities	
46	Architectural and engineering activities; technical testing and analysis	
47	Scientific research and development	
48	Advertising and market research	
49	Other professional, scientific and technical activities; veterinary activities	
52	Education	
54	Other service activities	
55	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	
56	Activities of extraterritorial organizations and bodies	
50	Administrative and support service activities	Defense & Social Management
51	Public administration and defence; compulsory social security	
53	Human health and social work activities	