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Understanding the Sustainability of the Energy–Water–Land Flow Nexus in Transnational Trade of the Belt and Road Countries

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Abstract: Increasing economic and population growth has put immense pressure on energy, water and land resources to satisfy national and supra-national demand. Through trade, a large proportion of such a demand is fulfilled. With trade as one of its key priorities, the China Belt and Road Initiative is a long-term transcontinental investment program. The initiative gained significant attention due to greater opportunities for economic development, large population and different levels of resource availability. The nexus approach has appeared as a new viewpoint in discussions on balancing the competing sectoral demands. However, following years of work, constraints exist in the scope and focus of studies. The newly developed multi-regional input–output (MRIO) models covering the world's economy and its use of resources permit a comprehensive analysis of resource usage by production and consumption at different levels, and bring more knowledge about resource nexus problems. Using the MRIO model, this work simultaneously tracks energy, water and land use flows and investigates the transnational resource nexus. A nexus strength indicator is proposed which depends on ternary diagrams to grade countries based on their combined resources' use and sectoral weighting. Equal sectoral weighting is assigned. The analysis presented a sectorally balanced nexus approach. Findings support existing work by recognizing energy, water and land as the robust transnational connections, from both production and consumption points of view. Resource nexus issues differ from country to country owing to inequalities in industrial set-up, preferences in economic policy and resource endowments. The paper outlines how key resource nexus problems can be identified and prioritized in view of alternative and often opposing interests.

Keywords: multi-regional input–output; nexus; trade; Belt and Road

1. Introduction

In today's globalized world, increasing economic and population growth present distinctive challenges when it comes to safeguarding enough energy, water and land resources to satisfy national and supra-national demand. Trade and imports fulfill an increasing share of that demand [1]. Resources therefore need to be managed more sustainably [2]. The independent treatment of water, energy and land systems may lead to the formulation and implementation of ineffective policies and actions. Efficient methods that take into account the interdependencies of resource use are thus required.

With trade as one of its key priorities, the China Belt and Road Initiative is a long-term transcontinental investment program. In 2013, China unveiled its plans to build a Silk Road Economic Belt and a 21st Century Maritime Silk Road (known as the "Belt and Road"—indicated as BRI hereafter), which immediately attracted worldwide attention [3,4]. It is predicted that this scheme will improve resource movements and trade efficiency by connecting more than 65 countries, which represent around 62% of the global population, about 35% of the global trade and over 31% of the world's GDP [5]. Studies have reported that trade and economic expansion may contribute to environmental degradation [6,7]. Since numerous countries along the BRI are not as developed as China, doubts exist that China's international trade and investment may lead to transferring resource exploration and environmental pressures to less-developed regions. The transnational trade networks can have serious consequences on demand for energy, water and land resources. More importantly, resources are interlinked, and any single-sector interventions may cause unintended side-effects in other sectors. At present, some studies associated with the BRI have been conducted linked to virtual water [8], energy efficiency [9], trade impacts [10] or carbon emissions [11]. Mostly, studies concentrated on single resource categories in supply chains and did not perform integrated assessments. To avoid the assumption of unsustainable development patterns and to promote fruitful models of sustainable cooperation, policies based on integrated research are required to allow more balanced use of natural resources.

In recent times, the nexus approach has become an especially important perspective among researchers. The Bonn 2011 nexus conference promoted the idea of a nexus, where the overall issues concerning economic development were understood from the viewpoint of the water–energy–food nexus. Nexus thinking prevents the negative consequences of a single resource development policy and improves resource use efficiency. However, hardly any consensus has emerged on the nexus meanings, with varying interpretations in different disciplines, in diverse situations and by different scholars [12,13]. The absence of a defined framework renders it difficult to determine what produces an efficient assessment of nexus, and presents major problems when formulating nexus-oriented plans. That is to say, it has been challenging to decide how to implement the nexus and formulate workable solutions [14].

The nexus research can be carried out from different viewpoints, depending on the sector in question. From the water point of view, energy and food are generated (as output) and water is an input resource. From the energy point of view, food is produced, but water may either be input, as in the case of hydroelectricity, or sometimes output, when energy is utilized in the treatment of water. If the food point of view is adopted, resource inputs are energy and water [15]. In any situation, the viewpoint considered will influence the policy design. This is attributed to different sector preferences as well as the data and knowledge. Considering the existing approaches to the resource nexus, the two-sector nexus concept, as water–energy [16], is common, and the three-sector nexus, as water–energy–food [17], is the most commonly recognized nexus concept in research and policy-making groups. The three-sector nexus often disregards the position of the land component. In accordance with other researchers [18,19], land involvement in a resource nexus approach can be regarded as vital due to its important ecological functions. Land plays a key role in nutrient recycling, production of food and water, supply of energy and provides resources for livelihood and development. It is very challenging to take an integrated view of these interrelated matters, given that nexus problems occur in different ways in different regions, with different resources and technology applications, governance and development priorities. Thus, for sustainable management of resources, an effective method should be one that can measure resource flows and interdependencies.

Input–output analysis (IOA) in conjunction with newly developed worldwide multi-regional input–output (MRIO) databases [20,21], with their extensive worldwide coverage of industrial interlinkages and usage of resources, may provide novel insights into the resource nexus. Such databases explain inter-industry links inside state economies and across foreign trade. Additionally, they are built with greater sector-based information and ecological stress depiction [22]. The databases enable analysis of resource nexus problems for all industries and different resources and to look deeper at their economic factors from the viewpoints of production as well as consumption. The ground-breaking work on the relationship between nexus structure and IOA mainly used case studies to tackle the nexus between energy and water resources. Of which, Marsh [23] proposed numerous input–output procedures, such as linkage, multiplier and dependence analysis, for dealing with various aspects of nexus problems. In recent times, and in the view of growing interregional and foreign trade significance, nexus scholars utilized MRIO and ecological network analysis (ENA) to investigate structural features and sectoral relations of economic networks [1,24,25].

In this manuscript, we establish a quantitative indicator for transnational resource nexus analysis based on the MRIO model. This indicator is used to compare and grade resource nexus issues resulting from transnational economic activities involving production as well as consumption. The indicator named as nexus strength in this study attempts to classify key resource nexuses on the basis of combined absolute resources' use. In other words, which resource nexuses of a country add more towards the transnational use of natural resources? This article aims to contribute primarily in two ways to the present understanding and management of the nexus problems. Firstly, the MRIO application enables the analysis of potentially ignored nexuses and related synergies and co-benefits. Secondly, a measurable indicator will help users to recognize the most complex nexuses, possibly assisting better sectoral and spatial scale analyses. The analysis presents the findings of an application in Belt and Road countries. The rest of the paper is structured as follows: Section 2 discusses the method, nexus strength indicator, ternary diagram and data, Section 3 presents the key results, and then the results are discussed in Section 4, and finally, Section 5 concludes the paper.

2. Method

2.1. Multi-Regional Input–Output Modeling (MRIO)

Up to now, MRIO models are among the most frequently used methods to study the economic and resource interdependence between different regions [26]. The input–output analysis (IOA) is based on data contained in IO tables. Each entry in the i-th row and j-th column demonstrates the flow from the i-th sector to the j-th sector. The IOA, composed by N linear equations, describes the production of a set of N economic sectors, as denoted in Equation (1):

$$x_i = \sum_{j=1}^{N} z_{ij} + y_i \quad (1)$$

where, N stands for the number of sectors in an economy, x_i represents the total output of the i-th sector, y_i is the final demand of sector i, while z_{ij} is the monetary flow from the i-th sector to the j-th sector. The MRIO model extends the standard IOA matrix to a bigger economy, which involves each sector in each country or region having a separate row and column. The MRIO denotes all of the input–output interactions of the defined economy.

The key input–output balance can be written in matrix form as follows:

$$\begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & A^{13} & \dots & A^{1m} \\ A^{21} & A^{22} & A^{23} & \dots & A^{2m} \\ A^{31} & A^{32} & A^{33} & \dots & A^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & A^{m3} & \dots & A^{mm} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{pmatrix} + \begin{pmatrix} \sum_s y^{1s} \\ \sum_s y^{2s} \\ \sum_s y^{3s} \\ \vdots \\ \sum_s y^{ms} \end{pmatrix} \quad (2)$$

where, coefficient matrix A depicts the intermediate input matrix across sectors and regions. Vector x shows the total output of each economic sector in each region.

The mathematical structure of embodied environmental impacts with respect to energy, water and land use can be expressed as:

$$E = R_e(I - A)^{-1}Y \tag{3}$$

$$W = R_w(I - A)^{-1}Y \tag{4}$$

$$L = R_l(I - A)^{-1}Y \tag{5}$$

where, E, W and L represent the embodied energy, water and land matrix induced by the final demand of the whole economic system. R_e, R_w and R_l are the diagonal matrices, representing the pressure coefficient of energy, water and land consumption. The diagonal elements are the direct energy consumption coefficient (R_{ei}), direct water consumption coefficient (R_{wi}) and direct land consumption coefficient (R_{li}). $L = (I - A)^{-1}$ is the Leontief inverse matrix, that captures both direct and indirect inputs. Y is a diagonal matrix, whereas the diagonal element Y_j shows the final demand of products and services in the sector j.

2.2. Nexus Strength Indicator

The nexus approach has constituted the focus of numerous research activities, but there is a lack of agreement on suitable methods to tackle the multidimensionality of the nexus [27]. Scholars have debated that current nexus frameworks mostly remain as partially preferring one sector over others [16,28]. More efforts are required to streamline nexus methods and concepts for policy-makers to make them widely available and usable [17]. So far, different approaches have analyzed the complex interactions between water, energy and food [27,29–32], yet methods vary significantly in their goals, scope and perspective. Some studies applied several performance indicators to assess nexuses among resources, mostly from consumption and intensity perspectives. For instance, they included the energy consumption rate of water [33] or the energy return spent on water [34]. A few program-based indexes were also implemented that concentrated on the weight and reliance of the social economic structure [35,36]. However, no current quantitative measures are easily acceptable to compare resource nexuses concerning numerous resources and countries at the same time. We tackle such problems in this article through ternary diagrams and sectoral weighting. Equal sectoral weighting is assigned via the average method (1/3 each). The ternary diagrams approach is very advantageous and relevant for resource nexus analysis provided the meaning of each line in the diagram is carefully understood.

Ternary diagrams used as graphic tools deal with the multiple resource issues. The nexus ternary diagram has three resources: energy (E), water (W) and land (L). An equilateral triangle represented these resources, where each corner of the triangle represents one of the resources, E, W or L, and each side represents a binary resource system. The location of a point within the internal area of the triangle promptly provides a series of information. Lines that cut the point position represent aggregated use of a given resource. The size of each point/circle inside the triangle shows the combined usage of the three resources (from 0 to 1). Ternary diagrams ensure to present all possible resource use combinations (for nexuses). The combination of any points on the ternary plot can be decided by reading from 0, along the basal line at the bottom of the diagram, to 1 (or 100 percent) at the apex of the triangle. The result of the ternary diagram is labeled as the nexus strength of a specific country. Following this approach, we can evaluate which country has a high nexus strength.

Mathematically, the summation of nexus strength for each country/sector can be expressed as:

$$Nexus\ strength = p_w d_{w,i} + p_e d_{e,i} + p_l d_{l,i};\ with\ i \in I\ ; I = \{1, \ldots, n\} \tag{6}$$

$$d_{w,i} = \frac{g_{w,i}}{g_w}\ ;\ g_w = \max(\{g_{w,i}\})_{i \in I} \tag{7}$$

$$d_{e,i} = \frac{g_{e,i}}{g_e} \ ; \ g_e = \max(\{g_{e,i}\})_{i \in I} \tag{8}$$

$$d_{l,i} = \frac{g_{l,i}}{g_l} \ ; \ g_l = \max(\{g_{l,i}\})_{i \in I} \tag{9}$$

$$\sum_{R}^{n}(p_n) = 1\,; R = \{w, e, l\} \tag{10}$$

where, w, e and l stand for water, energy and land respectively, i stands for each industry and I represents the set of all industries. Taking water as an example, $g_{w,i}$ represents the water consumption of industry i, g_w represents the largest industrial water consumption among all industries, $d_{w,i}$ represents the deviation between the largest industrial water consumption and water consumption of industry i, p is a weight that determines the relative importance of a given resource and p_w represents the weight of a water resource.

2.3. Reading Ternary Diagrams

For convenience in reading, it is necessary to understand certain ways and rules related to the use of ternary diagrams. Widely used in physical sciences, phase diagrams express equilibrium states in which two or more phases of matter exist together in solutions or in pure substances. Initially, Gibbs proposed the phase rule for multi-component analysis of a system [37], which in the literature is known by different names, such as ternary graph, triangle plot, Gibbs triangle or de Finetti diagram. For reading, the points below should be considered (follow Figure 1):

(1) In Figure 1a, each vertex of the equilateral triangle denotes 1, or 100% of one element, and 0% of the remaining two elements. Point '*x*' within a triangle represents a three-resource system. The three lines (*EW*, *WL*, *LE*) connecting the vertexes represent the combinations of *E*, *W* and *L*, and they represent a binary system. When moving along the edge of the diagram so as to symbolize the concentrations in a binary system, it is not important whether we advance in a clockwise or anticlockwise direction, as long as we are constant. For instance, take side *EW*: if we go in the direction of *W*, it denotes a binary system of *E* and *W*, having increasing concentrations of *W* and correspondingly decreasing concentrations of *E*, likewise for *WL* and *LE*.

(2) The ternary diagram may be ruled with lines parallel to the sides, and the composition at different points can then be read directly (Figure 1b). For instance, to find the pattern of *E*, *W* and *L* at position '*a*' in the triangle, the triangle side *EL* opposite to vertex *W* signifies a binary system comprised of *E* and *L*, in which the concentration of *W* is zero. The lines drawn parallel to side *EL* show increasing *W* from 0% to 100%, and the line that cuts '*a*' is equal to 15% of *W* and 85% of *E* + *L*. Likewise, along the line *EW*, $L = 0$. The lines parallel to *EW* illustrate increasing the concentration of *L* from 0% to 100%. The line parallel to *EW* that cuts '*a*' is equal to 20% of *L*. Hence, *E* can be calculated as $100 - (W + L) = 100 - (15 + 20) = 65\%$. Other examples shown in Figure 1b are: point $b = 30\%E + 20\%W + 50\%L$ and point $c = 0\%E + 60\%W + 40\%L$.

(3) Any line which is parallel to any side of the triangle represents the ternary systems in which the proportion of any one component is constant (in Figure 1c, example '*gh*'). In this particular situation, *E* is constant and the composition of *W* and *L* is changing.

Though our ternary diagram approach is simple in nature, it is versatile to be extended in a variety of ways related to research on the resource nexus. These extensions can be incorporated through weighing's and objectives. The suggested nexus strength provides a simple depiction of the important resource nexuses in the economic system. Nonetheless, the operational value of this indicator will rest on the particular local ecological, economic and political situation.

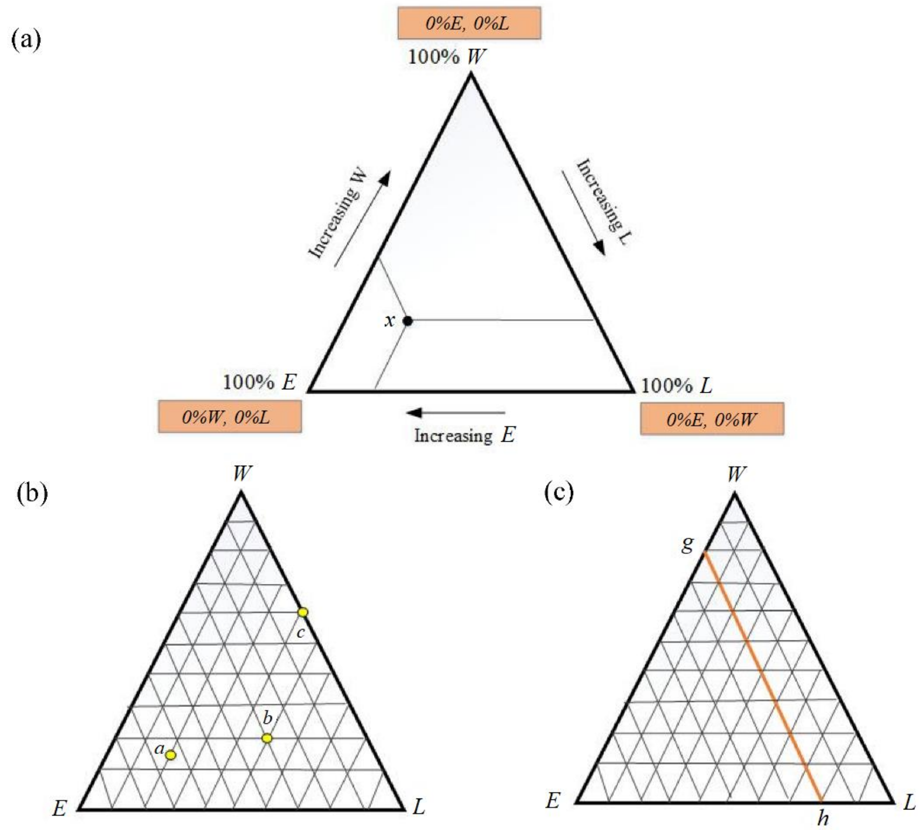

Figure 1. Representation of ternary diagram. (**a**) three-resource system, (**b**) the composition at different points, (**c**) line parallel to any side of the triangle.

2.4. Data Source

The current study utilizes energy, water and land use data of World Input Output Database (WIOD) satellite accounts. The database encompasses 27 EU countries and 13 other important countries worldwide, plus an aggregated region named as Rest of the World (RoW), with 35 sectors per region [21]. The study considers primary energy usage (referred to as energy flow), blue water and green water use, except gray water (water flow), and land usage, i.e., arable area, permanent crops, pastures and forest area (land flow). The BRI is a global open cooperation initiative, welcoming the participation of countries. Therefore, there are no specific boundaries. From WIOD, only those countries were considered that fall along the BRI. Thus, we were able to analyze only 15 Belt and Road countries in the current study. The research year is 2010 considering the availability of environmental accounts. The specific research scope and the names of the associated regions are presented in Table 1. Information on sectors' aggregation can be found in the Appendix A (see Table A1).

Table 1. Selected countries along the Belt and Road.

Section	Specific Regions	Total
East Asia	China, South Korea	2
South East Asia	Indonesia	1
North Asia	Russia	1
South Asia	India	1
Central and Eastern Europe	Bulgaria, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia, Slovenia	10

3. Results

3.1. Interwoven Trade Relations among Economies

This section presents the current intertwined trade relations of energy, water and land use between the BRI countries (excluding the rest of the world). In the first three figures, the fifteen regions are represented around a circle. The trade volume of each region is represented by the corresponding arc length around the circle, while chords, representing different economy couplings, represent the overall bilateral trade relations.

Figure 2 demonstrates the relations between these fifteen economies in transnational trade flows of energy. Among these flows, the largest one was related to South Korean exports to China. In particular, about 7.48 $\times$ 10^4 Kiloton of coal equivalent (Ktce) of embodied energy was exported from South Korea, of which 72% was exported to China. Meanwhile, China also exported a considerable amount of embodied energy to South Korea and India.

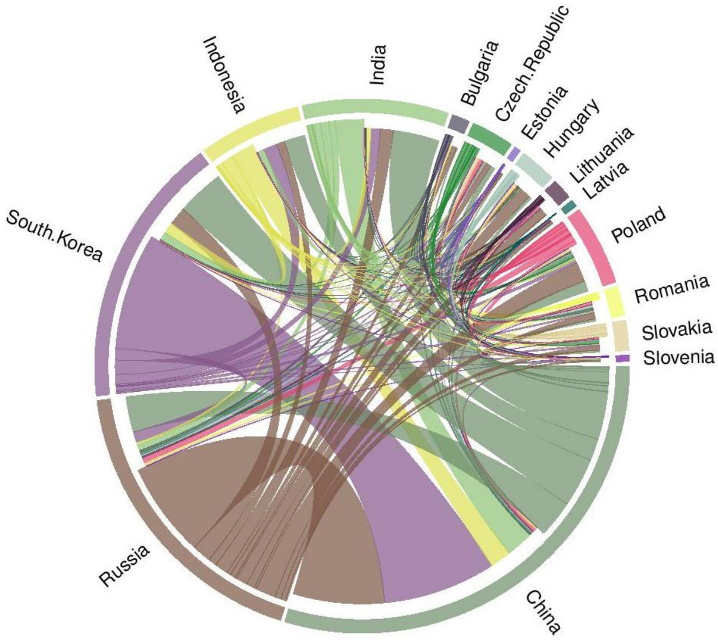

Figure 2. Interlinked relations of energy use between the fifteen economies in trade (excluding RoW).

As the second largest economy in the world, China needs huge amounts of energy imported from foreign countries. China imported about 1.26 $\times$ 10^5 Ktce of embodied energy in total, making it the largest importer of embodied energy among the fifteen countries. China largest energy flow associated with its imports occurred in its trade with Russia, 4.38 $\times$ 10^4 Ktce, accounting for 34% of its total imports. According to the analysis, China was the leading receiver of embodied energy from South Korea and Russia. This demonstrates that South Korea and Russia were the most significant trade partners of China for embodied energy. Notable export–import pairs supporting large energy flows were South Korea–China, Russia–China, China–India and Indonesia–China.

The transnational trade flows of water between selected countries are presented in Figure 3. The biggest flow was associated with the Indian exports to China. Around 1.83 $\times$ 10^4 Million ton (Mt) of embodied water was exported from India, of which 60% went to China. In addition, China was a prominent receiver of embodied water from Indonesia and Russia. As illustrated, among the countries, China also served as a supplier. China exported about 1.79 $\times$ 10^4 Mt of embodied water, of which 25% went to Russia and 24% to South Korea, respectively. Major export–import pairs supporting large water flows were India–China, Indonesia–China, Russia–China and China–South Korea.

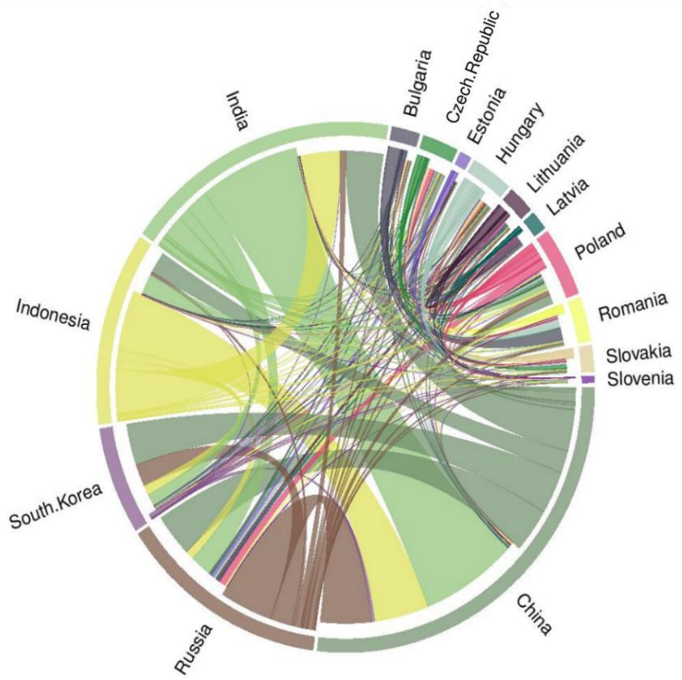

Figure 3. Interlinked relations of water use between the fifteen economies in trade (excluding RoW).

The transnational trade links of embodied land between these economies are portrayed in Figure 4. It can be seen that the largest flow was related to Chinese exports to Russia. About 1.47×10^4 Kilo hectare (Kha) of embodied land was exported from China, of which 59% went to Russia and 13% to South Korea. However, China also imported a substantial amount of embodied land from Russia and India (59% and 21%, respectively), where South Korea was the prominent receiver of embodied land from Russia. Major export–import pairs supporting large land flows were China–Russia, Russia–South Korea, China–South Korea and India–China. As can be understood, regions such as China, India, Russia and South Korea, etc., serve as hubs in transnational trade, that play key roles in both global exporting and importing markets.

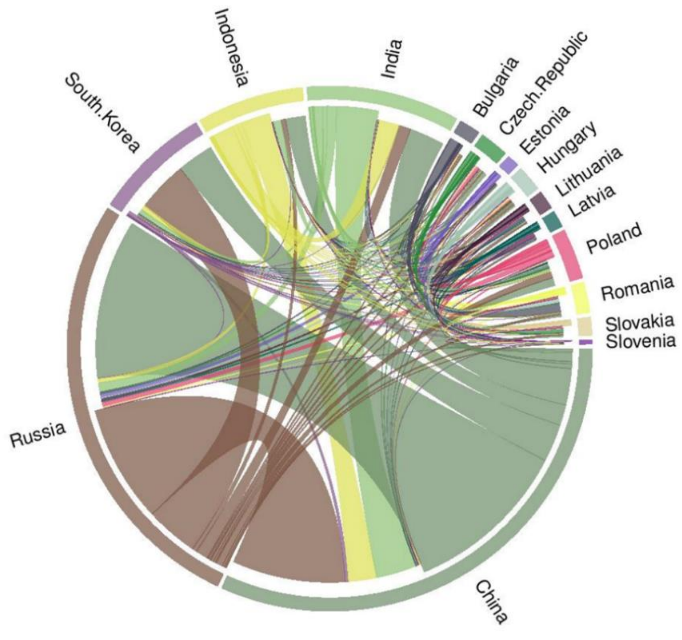

Figure 4. Interlinked relations of land use between the fifteen economies in trade (excluding RoW).

3.2. Self-Sufficiency by Source and Sink

This section presents the energy, water and land use self-sufficiency rates by sources and sinks, assessed through the indicators defined in an earlier study for arable land use [38]. Regions within the world economy extract different resources (energy, water and land) from the local environment and offer these resources for their own or foreign regions' final use. Thus, for each region, the self-sufficiency rate by source can be defined as the ratio of a resource (i.e., energy, water or land) exploited locally for its own final use to the total available resource (i.e., energy, water or land) exploited locally. For each region, this rate evaluates the contribution of local energy, water or land resources to its final consumption. Correspondingly, for a sink region in the supply chain, numerous resources are needed to satisfy its final demand. Along with the local environment, energy, water and land resources are also imported from overseas partners. The self-sufficiency rate by sink of a region can therefore be defined as the ratio of a resource (i.e., energy, water or land) exploited locally for its own final use to the region's resource (i.e., energy, water or land) use represented by resource use embodied in the goods used as its final consumption.

With respect to energy, China and India displayed the maximum energy self-sufficiency rate by source (see Table 2), being respectively 81.56% and 81.18%. This indicates that, from the supply side, most of the energy resources extracted from the local environment were used for domestic final consumption. Russia was a major energy source, having a rate of 63.16%. Thus, it served as a region that mostly provided energy resources to foreign countries. As the largest sink regions, the energy self-sufficiency rates for China and India were high, representing 83.66% and 82.96% of embodied energy in China and India's final use. This energy was self-provided. Conversely, for South Korea, being among the largest sink regions, the rate was 60.53%, illustrating that major energy resources embodied in South Korea's final use were imported from abroad. For some European regions, such as Latvia and Slovenia, their energy use self-sufficiency rates by source were respectively 64.92% and 57.78%, while those by sink were respectively 33.44% and 31.50%. Countries as a beneficiary of foreign resources would suffer the biggest impact, if these countries ran into supply problems.

Table 2. Self-sufficiency rate of selected countries along the BRI route by source and sink.

Region	Self-Sufficiency Rate by Source			Self-Sufficiency Rate by Sink		
	Energy	Water	Land	Energy	Water	Land
China	81.57%	86.93%	89.26%	83.66%	79.92%	79.35%
Russia	63.17%	91.36%	93.09%	88.74%	79.88%	86.76%
South Korea	51.41%	84.84%	82.07%	60.54%	24.81%	14.98%
Indonesia	61.01%	87.06%	87.06%	57.90%	93.74%	81.96%
India	81.19%	90.69%	90.60%	82.97%	96.19%	89.07%
Bulgaria	48.46%	46.79%	46.62%	61.07%	75.03%	65.83%
Czech Republic	52.43%	55.58%	63.83%	56.28%	46.05%	49.14%
Estonia	48.67%	38.48%	38.74%	47.69%	59.34%	55.78%
Hungary	52.26%	53.34%	53.17%	44.92%	75.38%	60.14%
Lithuania	46.29%	51.73%	73.40%	45.06%	74.92%	78.24%
Latvia	64.92%	63.44%	60.76%	33.44%	69.13%	73.43%
Poland	61.86%	69.77%	77.46%	60.61%	67.28%	64.81%
Romania	72.84%	83.83%	83.55%	64.56%	83.05%	81.26%
Slovakia	46.56%	63.72%	61.17%	49.48%	46.21%	28.61%
Slovenia	57.78%	67.03%	74.79%	31.50%	36.50%	37.00%

Regarding water, India and China, being the largest sources, had the maximum water self-sufficiency rates (90.69% and 86.92%), showing that the vast majority of water resources extracted in the two regions were mostly used to satisfy their own final requirements. As a sink region, the rate was much higher for India, with 96.18% of embodied water in

India's final use being self-provided. For China, being among the largest sink regions, its self-sufficiency rate by sink was 79.92%, showing that more than 20% of its water use was dependent on resources from foreign areas. An interesting situation is noted for South Korea, whose water use self-sufficiency rate by source and that by sink were respectively 84.84% and 24.80%. As witnessed, the welfare with respect to domestic water resources was almost preserved within this country, while more than 75% of the water use originated from abroad.

With regard to land, for China and Russia, being the largest exploiters of land resources, their land use self-sufficiency rates by source were respectively 89.26% and 93.08%, while those by sink were 79.34% and 86.75%. For India, its land self-sufficiency rates by source and by sink were 90.59% and 89.06%. In contrast, South Korea showed some interesting features, since its land use self-sufficiency rates by source and that by sink were 82.06% and 14.97%. This indicates that countries' land use mainly depended on resources from foreign areas. The increasing resource needs of South Korea's economy, as a country with limited resources, may influence this phenomenon.

3.3. Sectoral Contribution

Figure 5 shows the sectoral contributions to international trade of the top five net importers and exporters of energy, water and land resources' use in order to help understand the trade structure and resource balance in these regions.

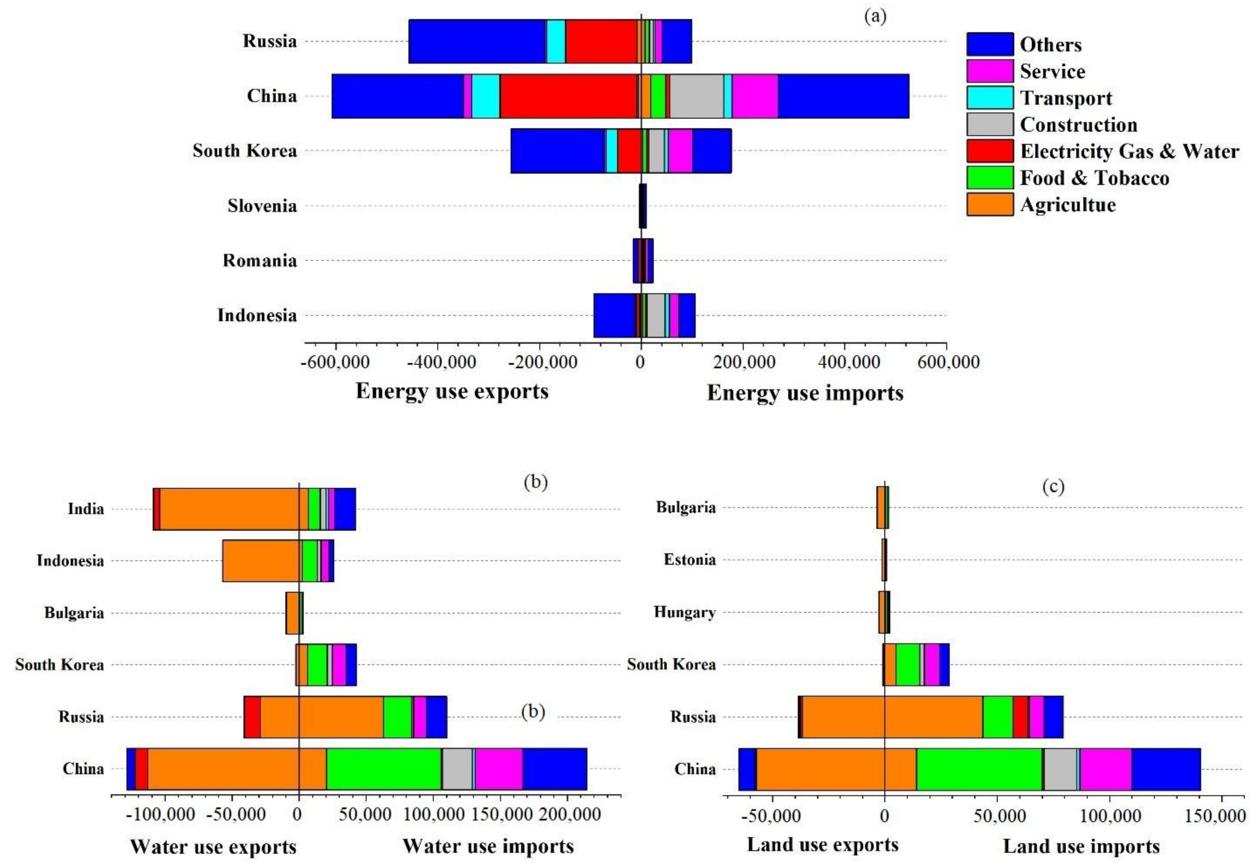

Figure 5. Sectoral contributions to trade of the top three net importers and exporters of energy–water–land use. (**a**) Energy, (**b**) water, (**c**) land.

Regarding energy, Indonesia, Romania and Slovenia appeared among the top three net importers in trade of energy use, while Russia, China and South Korea proved to be the three leading net exporters, as shown in Figure 5a. For Indonesia, the Construction sector shared the largest proportions (33.74%) of energy use embodied in Indonesia imports, followed by the others sector (30.10%), etc. The situation was similar for Romania and Slovenia, where the others sector remained the largest contributor to their imports of energy use, followed by the Service sector. As prominent net exporters of energy use in trade, Russia was dominated by the others sector (58.49%), whereas, for China, the Electricity Gas and Water sector (44.07%) dominated. Meanwhile, for South Korea, the others sector largely contributed to embodied energy exports. China had larger resource imports and exports, showing its significant role as a world trading center, with massive embodied resources flowing in and out.

Regarding water, China, Russia and South Korea were the top three net importers in trade of water use. Meanwhile, India, Indonesia and Bulgaria were the three leading net exporters, as shown in Figure 5b. For China, the Food and Tobacco sector shared the major proportion (39.66%) of water use embodied in China's imports, followed by the others sector (22.34%). For Russia, the Agriculture sector dominated, while, for South Korea, the Food and Tobacco industry remained the largest contributor to their water use imports. Meanwhile, the water use exports for India, Indonesia and Bulgaria were mostly related to the Agriculture sector, revealing their status as a resource-intensive economic structure.

With respect to land, China, Russia and South Korea were the top three net importers in trade of land use. Bulgaria, Estonia and Hungary were the three leading net exporters, as shown in Figure 5c. For China, the Food and Tobacco industry shared the biggest proportion (39.84%) of land use embodied in China's imports, proving China's intensive requirements for food products from foreign areas. For Russia, the Agriculture sector (55.04%), and for South Korea the Food and Tobacco industry (36.52%), remained the largest contributors to land use imports. With regard to land use exports, the Agriculture industry played a dominant role.

3.4. Nexus Strength by Country

The nexus strength by country can be seen in Figures 6 and 7. Findings of the research have been evaluated using equal weights, considering each resource as equally important. Thus, nexus strength only relates to the total use of resources. The findings are in line with the production-based view (territorial, i.e., represents resource usage inside national borders) and the consumption-based view (caused by final demand). For all country-level values, the same scaling factor is used, and thus they are comparable with one another. The nexus strength is somewhat consistent with domestic output levels, as large economies displayed high nexus strength, as shown by the point size within the nexus ternary diagram. Figure 6 illustrates the status of all countries from a production perspective, and activities mostly appear at the middle of the ternary plot. Particularly in China, the energy–water–land nexus seems to be strong, given the wide combined use of resources revealed by its point size in the plot. The lines that cut its position in the plot provide a series of information that can be used to compare its resource use composition with other countries. China used about 35% energy, 30% water and 35% land. This can be associated mainly with the role of its Others, Agriculture and Food industries. Nevertheless, the amount and accessibility of resources causes variations in the strength and makeup of these industries' related nexuses. Two other influential economies after China, i.e., Russia and India, also tend to have a strong connection between energy and water–land. However, they are somewhat at the margins of the plot, indicating a large use of a single resource compared to their use of the other two resources. As can be seen from lines that cut its point location, Russia used large portions of land, around 54%, while its energy and water usage was only about 22% and 24%, respectively. India used large portions of water, around 59%, while its energy and land usage was only about 18% and 23%, respectively. The agriculture industry, for example, in India, has many key drivers, including the existence of energy/gas reserves, domestic policy and technology. Figure 7 shows all countries' status from a consumption perspective. China maintained its large combined resource usage, i.e., about 34% energy, 33% water and 34% land. As for the two perspectives, there is hardly any big change noted. It may be because China is the world's second-largest economy, driving global production and consumption. Again, Russia is driven by large proportions of land, around 53%, while energy and water usage is only about 17% and 30%, respectively. India is largely water-driven, around 60%, while energy and land usage is only about 19% and 21%, respectively.

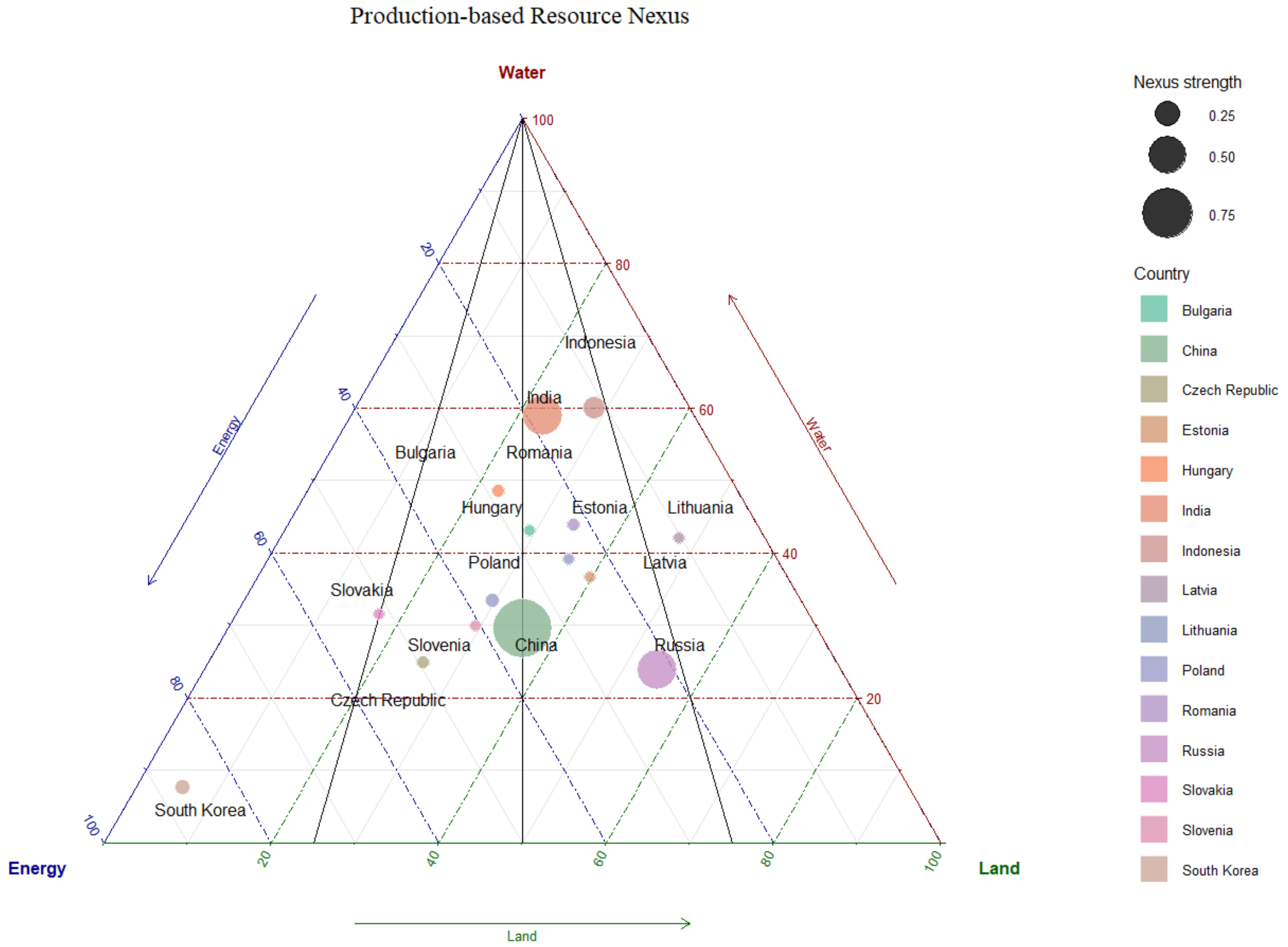

Figure 6. Nexus strength results by country based on the production viewpoint. Lines that cut the point position represent aggregated usage of a given resource. Size of the point/or circle inside the triangle shows the combined contribution of the three resources. Location of a point within the triangle provides a series of key information that can be used to compare its resource use combination with other countries.

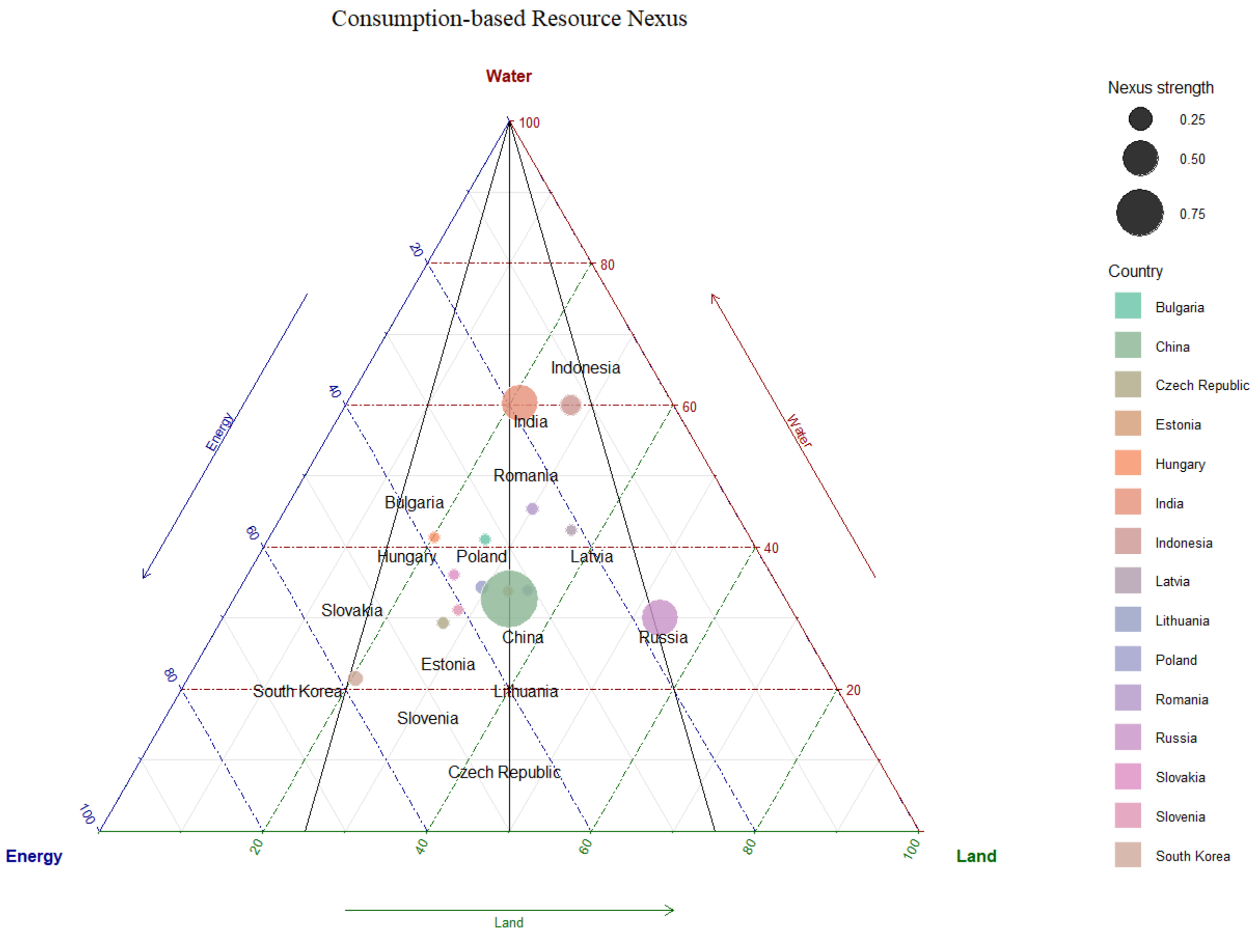

Figure 7. Nexus strength results by country based on the consumption viewpoint. Lines that cut the point position represent aggregated usage of a given resource. Size of the point/or circle inside the triangle shows the combined contribution of the three resources. Location of a point within the triangle provides a series of key information that can be used to compare its resource use combination with other countries.

4. Discussion

Restricted access to vital resources is increasingly seen as a significant impediment to sustainable development. Many technological processes, such as the production of energy and food, encounter resource supply vulnerability issues such as water constraints on energy and food production. Such constraints are usually linked to economic stability, organizational hurdles, political disputes and also the actual availability of supporting natural resources. The nexus concept was suggested in response to such challenges to assist in resource management practices [17].

The nexus focus presented in this work identified key areas of simultaneous resource usage in economic systems. The energy–water–land nexus seems to be strong in China, which is linked particularly to the role of its Others, Electricity and Agriculture industries. Tables A2 and A3 found in the Appendix A present the industrial structure that helps to explain the characteristics of the energy–water–land use flow of China. The second-strongest energy–water–land use flows are in India and Russia. For Russia, Others and Agriculture industries are the main contributors to land and energy use, while for India, Agriculture is the absolute direct contributor to water and land use. The suggested nexus strength indicator that depends on the ternary diagram provided a depiction of the important resource nexuses in economic systems. A point location inside the triangle provides prompt information which can be used to compare and grade resource nexus issues that arise from the transnational economic system. The method used is flexible and can be greatly expanded. The triangle properties, particularly lines and points, not only measure the actual circumstance of a given process, but can predict process behavior as well, based on any change in its driving forces. For example, if there is any sectoral interference, a shift of point position inside the triangle will be noted as well, and one can then test and study the best alternatives. Governments will have a strong tool in the decision-making process on sustainable development for setting policies and selecting alternatives that supersede conventional sectoral interventions.

Currently, the Belt and Road region is at the frontline of undergoing speedy development interventions on a wide scale. Isolated sectoral investment can result in valuing the priorities of one sector in particular over another. Policy actions can be taken in either of the energy, water or land sectors, and we presume that traditionally, decision-making has been solely independent and sector-specific in nature. Thus, the nexus viewpoint should be considered for inter-sectoral negotiations. The current study discussed a balanced nexus structure in the transnational context of the Belt and Road region, and identified important hotspots of simultaneous resource use and associated interlinkages. The use of a sectorally balanced nexus strategy (lowers biases associated with the sectors) serves as a tool to promote discussion to strengthen sectoral collaboration, to potentially accommodate investments that individual sectors would view as sub-optimal and eventually, to boost overall program outcomes.

Amongst all, China is the largest developing country by both population and economic size. Since the BRI was proposed by China, there are concerns that China's trade may lead to natural resource depletion and shifting of detrimental resource effects to neighboring countries. Such concern would certainly plague regional integration and economic cooperation. Thus, in the process of advancing the Belt and Road Initiative, China should develop investment strategies based on the nexus architecture. It is important to support and fund nexus-framed development decisions in the region for better resource management that will certainly help to eliminate misunderstandings. Future research should take on a more dynamic view of scenario development and modeling energy, water and land use flows in the Belt and Road region to provide important information on the resource nexus, so that strategies can be raised by considering the local realities.

Limitations of the Study

This study has some limitations with respect to the method and data. The MRIO model is for the year 2010, so the age of the available data is a significant shortcoming. Additionally, it does not capture trends, a problem that could be solved by using time series data. A number of ways were developed, incorporating multiple spatial scales (for instance, global, national and regional), to capture the regional heterogeneity within the global economy [39,40]. However, increased data inaccuracy is a major disadvantage, due to disaggregation approximations of trade flows from one area in one country to another area in another country. The limitations of IOA are well-documented in the literature [26,41]. For example, data uncertainty due to sectoral aggregation errors. In this research, sectors were aggregated into seven sectors for conformity, which could decrease the accuracy of the results.

As for nexus strength, its development mainly focused on the absolute use of resources, ignoring other aspects related to the nexus debate, i.e., resource availability and price. Additionally, the resource use alone does not necessarily entirely align with the significance of a given nexus issue.

5. Conclusions

Research based on MRIO allows the most detailed and systematic study of resource usage by production and consumption activities at different levels. These activities can trigger the simultaneous use of different resources in a variety of ways, which can be viewed as a kind of resource nexus. This work is placed more effectively to provide new insights into cross-sectoral dynamics and outlines how key resource nexus problems can be identified and given preference in view of alternative and often opposing interests. We established a nexus strength indicator which basically uses ternary diagrams to grade countries based on their combined resources' use and sectoral weighting. Equal sectoral weighting was assigned. In the context of Belt and Road, the findings only provide a snapshot of the transnational resource nexuses' enormous diversity and complexity. However, the overall patterns found can be used to guide future study and resource management activities.

The notion that resources' flow in trade commodities has the ability to challenge environmental policies is supported by various research investigations. The current approach showed that it is possible to evaluate the resource burdens of a region's consumption rather than just production, within its territories. It helped to identify the key regions or industrial sectors that dominate nexus flows, and thus should be prioritized to enhance resource utilization efficiency and lower resource burdens. Further, this study confirmed that drivers of resource consumption can originate from beyond national boundaries. The resource nexus issues are not the same among countries due to disparities in industrial structure, trade policy priorities and resource endowments. Thus, nexus work could disclose different nodes of interest for different countries.

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Appendix A

Table A1. 35 sectors aggregated into 7 sectors.

Code	7 Sectors	35 Sectors
1	Agriculture	Agriculture, hunting, forestry and fishing
2	Food and Tobacco	Food, beverages and tobacco
3	Electricity Gas and Water	Electricity gas and water
4	Construction	Construction
5	Transport	Inland transport
		Water transport
		Air transport
		Other supporting and auxiliary transport activities; activities of travel agencies
6	Services	Hotels and restaurants
		Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel
		Wholesale trade and commission trade, except of motor vehicles and motorcycles
		Retail trade, except of motor vehicles and motorcycles; repair of household goods
		Post and telecommunications
		Financial intermediation
		Real estate activities
		Renting and other business activities
		Public admin and defence; compulsory social security
		education
		Health and social work

Table A1. *Cont.*

Code	7 Sectors	35 Sectors
7	Others	Other community, social and personal services Private households with employed persons Mining and quarrying Textile and textile products Leather and footwear Wood and products of wood and cork Pulp paper, printing and publishing Coke-refined petroleum and nuclear fuel Chemical and chemical products Rubber and plastics Other non-metallic minerals Basic metals and fabricated metals Machinery Transport equipment Electrical and optical equipment Manufacturing and recycling

Table A2. Industrial structure of production-based energy–water–land use flow of China in 2010.

Sector		Total		Local Consumption		International Export			
								Main International Export Regions	
		SPB	SPB/NPB (%)	LCP	LCP/SPB (%)	IEB	IEB/SPB (%)	Top Three Regions	Ratio (Region/IEB) (%)
Energy (Mtce)	Electricity	1.61×10^6	48.85	1.34×10^6	83.37	2.68×10^5	16.63	India, S.Korea, Russia	10.24
	Others	1.20×10^6	36.44	9.43×10^5	78.48	2.59×10^5	21.52	India, S.Korea, Russia	10.50
	Transport	2.60×10^5	7.88	2.04×10^5	78.55	5.58×10^4	21.45	S.Korea, India, Russia	8.77
	Subtotal	3.07×10^6	93.17	2.49×10^6	81.05	5.82×10^5	18.95	-	10.21
	Total for all sectors (NPBE)	3.30×10^6	100	2.69×10^6	81.57	6.08×10^5	18.43	-	18.43
Water (Mt)	Agriculture	9.04×10^5	91.90	7.91×10^5	87.53	1.13×10^5	12.47	Russia, S.Korea, India	10.32
	Electricity	4.71×10^4	4.79	3.77×10^4	79.93	9.46×10^3	20.07	S.Korea, India, Russia	10.07
	Others	2.11×10^4	2.14	1.52×10^4	71.99	5.91×10^3	28.01	India, S.Korea, Russia	10.29
	Subtotal	9.72×10^5	98.84	8.44×10^5	86.82	1.28×10^5	13.18	-	10.30
	Total for all sectors (NPBW)	9.84×10^5	100	8.55×10^5	86.93	1.29×10^5	13.07	-	13.07
Land (Kha)	Agriculture	5.92×10^5	97.93	5.35×10^5	90.34	5.72×10^4	9.66	Russia, S.Korea, India	10.28
	Others	8.49×10^3	1.40	1.41×10^3	16.56	7.09×10^3	83.44	Russia, India, S.Korea	93.16
	Transport	2.48×10^3	0.41	1.99×10^3	80.40	4.86×10^2	19.60	S.Korea, India, Russia	8.81
	Subtotal	6.03×10^5	99.75	5.39×10^5	89.26	6.48×10^4	10.74	-	19.34
	Total for all sectors (NPBL)	6.05×10^5	100	5.40×10^5	89.26	6.49×10^4	10.74	-	10.74

Note: Taking energy as an example, PB refers to PBE: production-based energy; SPBE: sectoral production-based energy; NPBE: national production-based energy; LCP: production-based energy used for local consumption; IEB: production-based energy embodied in international export; SPB = LCP + IEB; NPB = $\sum S_i PB$, i represents the sector.

Table A3. Industrial structure of consumption-based energy–water–land use flow of China in 2010.

	Sector	Total		Local Production		International Import			
		SCB	SCB/NCB (%)	LPC	LPC/SCB (%)	IIB	IIB/SCB (%)	Main International Import Regions: Top Three Regions	Main International Import Regions: Ratio (Region/IEB) (%)
Energy (Ktce)	Others	9.97×10^5	31.01	7.41×10^5	74.27	2.57×10^5	25.73	S. Korea, Russia, India	19.99
	Construction	9.33×10^5	29.01	8.27×10^5	88.63	1.06×10^5	11.37	S. Korea, Russia, India	20.51
	Services	5.82×10^5	18.09	4.92×10^5	84.49	9.02×10^4	15.51	S.Korea, Russia, Indonesia	20.60
	Subtotal	2.51×10^6	78.10	2.06×10^6	81.97	4.53×10^5	18.03	-	20.24
	Total for all sectors (NCBE)	3.22×10^6	100	2.69×10^6	83.66	5.25×10^5	16.34	-	16.34
Water (Mt)	Agriculture	3.76×10^5	35.09	3.55×10^5	94.55	2.05×10^4	5.45	India, Indonesia, Russia	6.30
	Food andTobacco	2.91×10^5	27.17	2.05×10^5	70.69	8.52×10^4	29.31	India, Indonesia, Russia	9.15
	Services	1.48×10^5	13.85	1.13×10^5	76.02	3.55×10^4	23.98	India, Indonesia, Russia	11.67
	Subtotal	8.14×10^5	76.10	6.73×10^5	82.66	1.41×10^5	17.34	-	9.37
	Total for all sectors (NCBW)	1.07×10^6	100	8.55×10^5	79.92	2.15×10^5	20.08	-	20.08
Land (Kha)	Agriculture	3.05×10^5	44.83	2.91×10^5	95.37	1.41×10^4	4.63	Russia, India, Indonesia	3.05
	Food and Tobacco	1.65×10^5	24.19	1.09×10^5	65.99	5.60×10^4	34.01	Russia, India Indonesia	4.21
	Services	8.70×10^4	12.79	6.37×10^4	73.25	2.33×10^4	26.75	Russia, India, Indonesia	7.40
	Subtotal	5.57×10^5	81.81	4.63×10^5	83.22	9.34×10^4	16.78	-	4.83
	Total for all sectors (NCBL)	6.80×10^5	100	5.40×10^5	79.35	1.41×10^5	20.65	-	20.65

Note: Taking energy as an example, CB refers to CBE: consumption-based energy; SCBE: sectoral consumption-based energy; NCBE: national consumption-based energy; LPC: consumption-based energy for local production; IIB: consumption-based energy embodied in international import; SCB = LPC + IIB; NCB = $\sum S_i CB$, i represents the sector.

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