Unravelling the nexus: exploring the pathways to combined resource use

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Summary

In response to the unprecedented decline in global natural resource endowments, the so-called nexus framework is gaining increasing influence on resource management practices. In this research, we approach the resource nexus through the concept of nexus pathways. Nexus pathways are configurations that resource flows follow along supply chains leading to the combined use of two or more resources. Three general types of pathways are identified: direct (on-site use), dependent (one-way supply chains) and interdependent (supply chain feedbacks). We quantify and compare each pathway by means of multi-regional input-output analysis and structural path analysis, and apply this approach to a comparative case study on the water-energy nexus (WEN) in the United States (US) and China. Interdependencies or feedbacks are generally thought to be relevant for the WEN, especially between water and energy sectors. Our economy-wide analysis for both countries indicates, however, that feedbacks neither play an important role in the WEN nor substantially take place between water and energy sectors. The most important feedbacks contribute to less than 1% of total resource use, and these take place mostly between manufacturing sectors. Overall, the studied WEN is mostly driven by dependent pathways and, to a lesser degree, direct resource use. Comparative differences between the two countries are largely explained by differences in economic structure, technology, and resource endowments. Our findings call into question current research and policy focus, and suggests greater attention to less complex but more determining pathways leading to absolute resource use.

Keywords: water-energy nexus, input-output analysis (IOA), structural path analysis, resource management, feedback loops.

<heading level 1> Introduction

Global natural resource endowments are declining at unprecedented rates, in turn compromising economic development and well-being (Graedel and van der Voet, 2010; Smith, 2013). Some regions and industries have or are currently experiencing shortages of certain resources, such as freshwater and fertile land, leading to price increases, governance issues and social conflict (Andrews-Speed et al., 2012). It is widely accepted that resource management practices can benefit from integrated approaches such as the so-called “nexus framework”, which focuses on the interconnections between sustainability challenges, such as energy and food security, climate change, and air pollution across organizational levels (from local to international), space, and time (Liu et al., 2015). Interconnections may indicate a joint causation of several challenges or unintended side effects of overcoming challenges. When applied to the challenges related to the use of natural resources alone, some authors speak of the ‘resource nexus’ (Andrews-Speed et al., 2012). The advantage of this framework lays in the possibility to anticipate unforeseen consequences, identify trade-offs and co-benefits and find optimal solutions between competing interests (Bizikova et al., 2013; Howells et al., 2013). Such strengths have been acknowledged by several governments and international organizations for sustainable development and national security goals (Nexus, 2016; UN-Water, 2016). While widely recognized to support resource management policies, the (resource) nexus lacks clear definitions, making the concept somewhat ambiguous (Cairns and Krzywoszynska, 2016).

The resource nexus can be understood, broadly speaking, as the linkages between two or more resources. Such linkages can be due to natural phenomena (e.g. co-occurrence of zinc and lead in mineral deposits), driven by socio-economic systems (e.g. production and consumption activities) or a combination of both. Here, we focus on the linkages caused by the functioning of economic systems or, in other words, on the interactions between resources as a consequence of economic activity. In its simplest form, resource linkages relate to the direct requirement of resources as factors of production. The combined resource use can take place either as a result of naturally occurring 'coupling' of resources leading to co-production (e.g. zinc-lead deposits) and/or due to the physical properties of raw materials and the characteristics of the technologies that require them. For example, traditional agricultural systems have direct requirements of fertile land, nutrients and freshwater in order to produce food. On the other hand, some authors relate the nexus concept to the dependencies within the production system, for example the requirement of one resource to produce another or the substitutability of two or more resources (Andrews-Speed et al., 2012; Graedel and van der Voet, 2010). The most widespread definition, however, associates the nexus to the interdependencies between production systems, for example the mutual reliance between water and energy systems (Bazilian et al., 2011). There is therefore a degree of complexity involved in the definition of nexus issues: from direct to dependent and interdependent relationships (in ascending order of complexity).

In general, nexus studies tend to focus on complex relationships, as these present more analytical challenges (Liu et al., 2015; Villamayor-Tomas et al., 2015) and are expected to unveil previously unnoticed issues regarding resource use and security of supply (Cohen et al., 2004). Interdependencies or feedbacks are generally believed to play a major role in the most popular nexus frameworks (e.g. water-energy and water-energy-food nexus), by creating vicious circles which exacerbate issues related to resource use (Pate et al., 2007; Rasul and Sharma, 2016). The relative importance of such interdependencies in the context of global resource use is, however, not fully understood. In order to capture and compare all possible nexus pathways, we adopt a broader definition for the resource nexus which encompasses all types of relationships previously described. Nexus pathways are understood here as the pathways or configurations that resource flows follow along supply chains within a given economic system leading to the combined use of two or more resources, with a focus on identifying and weighting causal relationships: direct, dependent, and interdependent.

Relevant pathways leading to the combined use of resources within economic systems, whether based on direct, dependent or interdependent relationships, can be consistently approached through input-output analysis (IOA) (Leontief, 1970; Miller and Blair, 2009). Input-output (IO) databases describe economic inter-industry relationships in economic terms, and direct resource requirements can be easily included in the form of environmental extensions (Kitzes, 2013). It is thus possible to calculate the total resource requirements (direct plus indirect) resulting from economic activities, including trade. Recently constructed global multiregional IO (MRIO) databases (Miller and Blair, 2009; Tukker and Dietzenbacher, 2013) offer unprecedented insights in terms of spatial and sectorial scope, technology detail and environmental indicators. The multiple analytical possibilities of IOA have spurred an emerging literature dealing with various nexus issues, such as the land-water nexus in China (Guo and Shen, 2015), the water-energy nexus in China (Kahrl and Roland-Holst, 2008; Li et al., 2012; Okadera et al., 2015), the water-energy nexus in Australia (Marsh, 2008), and the global resource nexus (Font Vivanco et al., 2017), which confirms the value of this approach in nexus research. A literature review of IO tools used for the study of nexus issues can be found in Tukker and Font Vivanco (2017). Despite IOA's contribution to the understanding of nexus problems, the relative importance of the various pathways remains an outstanding issue.

Against this background, this article addresses the following research question: What are the most relevant pathways leading to the resource nexus? Answering this question will allow us to reflect on the relative importance of the different pathways leading to resource nexus problems, whether based on direct, dependent and interdependent relationships. Unraveling the (resource) nexus will also help to assess whether predominant research efforts on complex relationships are coherent with global resource decoupling goals, in turn contributing in the design of more effective resource management policies worldwide.

<heading level 1> Methods and data sources

<heading level 2> Nexus pathways

Input-output tables describe inter-industry relationships in terms of yearly economic flows. These relationships can be expressed graphically using nodes (*n*) and directed edges (*e*) that connect pairs of nodes and indicate the direction of flow. For example, $[n_1 \underset{e_{12}}{\longrightarrow} n_2]$ describes an economic flow e_{12} from node n_1 to node n_2. The collection of nodes and edges forms a network, which in the context of IOA represents the economic structure of a given economy. In turn, each node can be 'weighted' according to a given variable, for example the direct requirements of one or more resources (*r*). We can identify three general types of pathways according to the relationship between the nodes: direct, dependent and interdependent. Direct relationships are characterized by the absence of edges, and so resource use will take place within each node independently. Dependent and interdependent relationships contain edges, but differ in the fact that the former describes a one-way reliance either between the same node (self-inputs) or two different nodes, whereas the latter describes mutual or two-way reliance between two different nodes (feedbacks). A formal classification and examples are presented in Table 1. Pathways or sub-graphs within networks are often referred to as 'network motifs', and are especially useful to determine their influence on the overall function and efficiency of a network (Milo et al., 2002).

Let us consider an illustrative case with two nodes, n_1 and n_2, which are weighted (expressed within round brackets) according to resources r_1 and r_2 (see Figure 1). If we consider only direct relationships, there exist a total of nine possible nexus pathways (expressed within square brackets): $[n_1 (r_1, r_2), n_2 (r_1, r_2)]$, $[n_1 (r_1), n_2 (r_2)]$, $[n_1 (r_2), n_2 (r_1)]$, $[n_1 (), n_2 (r_1, r_2)]$, $[n_1 (r_1, r_2), n_2 ()]$,$[n_1 (r_1, r_2), n_2 (r_1)]$, $[n_1 (r_2), n_2 (r_1, r_2)]$, $[n_1 (r_1, r_2), n_2 (r_2)]$, $[n_1 (r_1), n_2 (r_1, r_2)]$. As we include edges, the number of possible nexus pathways grows exponentially, and the same is true when increasing the amount of nodes (Han et al., 2011). Looking at the previous nine possible combinations, however, we can observe overlaps. For instance, the pathway $[n_1 (r_1, r_2), n_2 (r_1, r_2)]$ includes both the pathway $[n_1 (r_1), n_2 (r_2)]$ and $[n_1 (r_2), n_2 (r_1)]$, as the use of a single resource, either r_1 or r_2, is not incompatible with the use of both resources r_1 and r_2 simultaneously. Overlaps will also take place between pathways containing different amounts of nodes. For example, the pathway $[n_1(r_1, r_2) \underset{e_{12}}{\longrightarrow} n_2(r_1)]$ will include both $[n_1 (r_1, r_2)]$ and $[n_1(r_2) \underset{e_{12}}{\longrightarrow} n_2(r_1)]$.

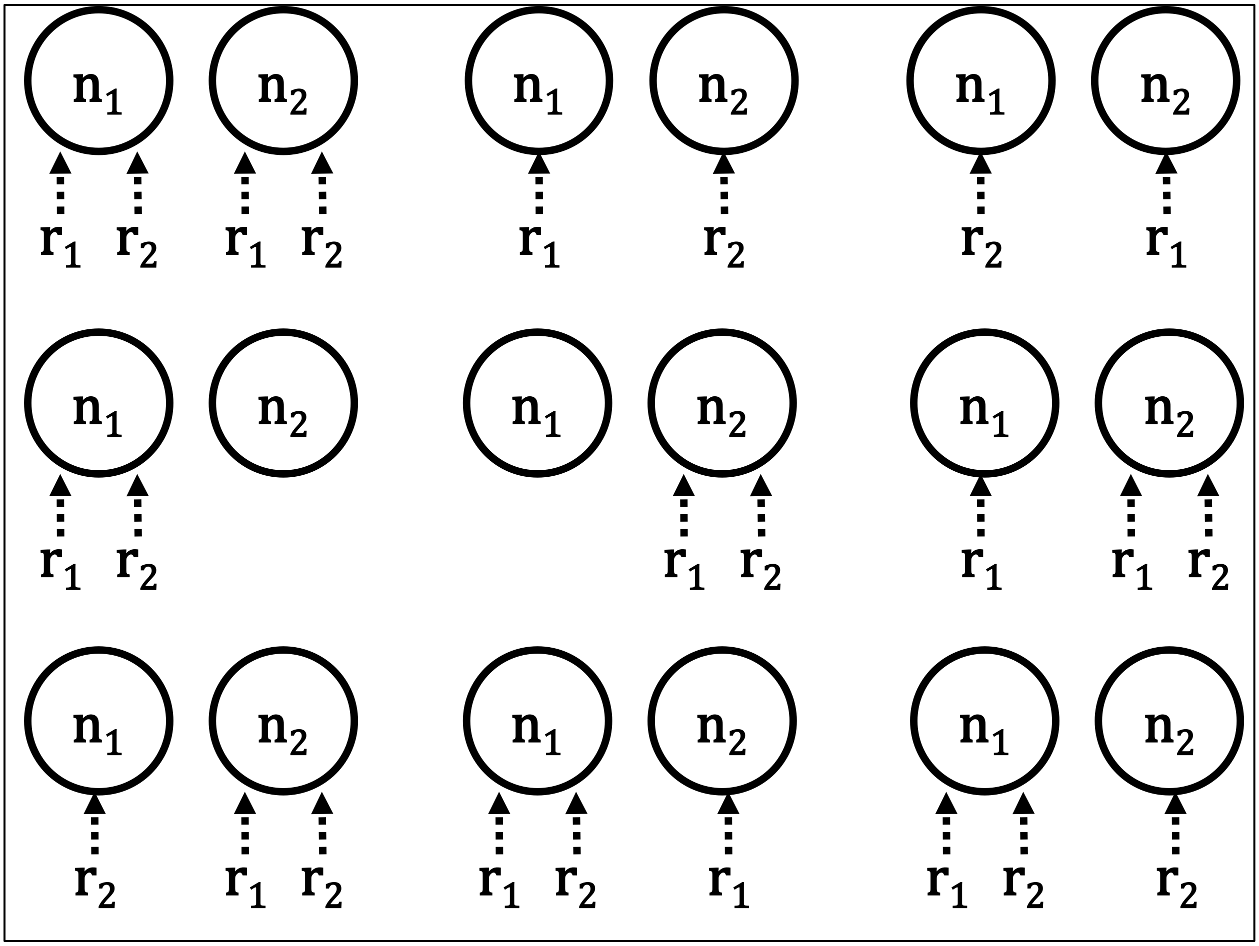
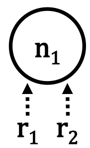
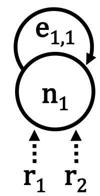
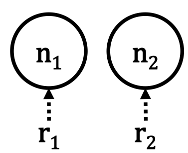
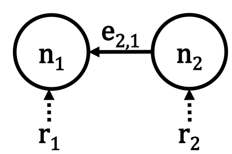
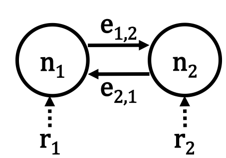


Figure 1. Illustrative case of possible nexus pathways leading to the simultaneous use of resources r_1 and r_2 for the case of two nodes, n_1 and n_2, considering only direct relationships.

One way to overcome the overlapping of pathways is to propagate a given resource through economic dependencies, such as that the propagation is uniquely targeted for and derived from a particular node (Fath and Patten, 1999). This permits to effectively decompose a given weighted network into unique pathways without the risk of double-counting. A common technique to extract the most relevant unique pathways is structural path analysis (SPA). Initially developed for the study of ecosystems (Fath and Patten, 1999), it was first applied to economic analysis by Defourny and Thorbecke (1984). A number of studies have applied SPA to study the most relevant pathways within economic IO systems for some environmental flows such as energy (Treloar, 1997), CO_2 emissions (Peters and Hertwich, 2006), GHG emissions (Acquaye et al., 2011) and other environmental flows (Lenzen, 2003). The relative importance of the different types of pathways (see Table 1) and its relationship to (resource) nexus issues, however, remains unaddressed. In the following sections, we describe an SPA method applied to identify and classify relevant nexus pathways.

		Relationship between nodes		
		Direct	**Dependent**	**Interdependent**
Number of nodes	**One**	*Self-interaction (1)*	*Self-loop (1)*	
				
	Two	*Self-interaction (2)*	*Chain (2)*	*Feedback loop (2)*
				
	Three	*Self-interaction (3)*	*Chain (3)*	*Feedback loop (3)*

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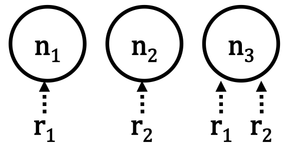
<td>
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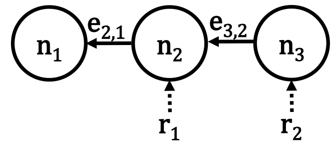
<td>
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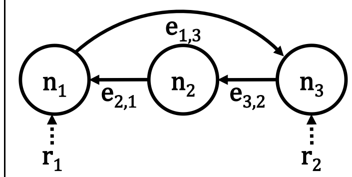
<td>
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Table 1. Examples of pathways involving three nodes (n_1, n_2 and n_3) leading to a nexus between resources r_1 and r_2. Within brackets, the amount of unique nodes involved.

<heading level 2> Structural Path Analysis

Using the standard demand-pull Leontief model (Leontief, 1970), the total factor requirement (e) from a given final demand is calculated as:

$$e_r = s_r x$$

$$with \ s_r = f_r \hat{x}^{-1};$$

$$x = (I - A)^{-1} y = Ly;$$

$$A = Z\hat{x}^{-1} \qquad (1)$$

Where subscript *r* indicates a given resource, *s* is an *1 × n* vector of direct factor requirements (*s*) per unit of economic output, being *n* the number of industries, *x* is an *n × 1* vector of economic outputs, *f* is an *1* x *n* vector of direct factor requirements used by each industry (in absolute terms), *A* is an *n × n* matrix of technical coefficients indicating the inter-industry inputs required to supply one unit of *x, I* is an *n × n* identity matrix, *y* is a *n* x *1* final demand vector, *L is* the Leontief inverse containing the multipliers for the direct plus indirect inter-industry inputs required to satisfy one unit of *y* and *Z* is an *n × n* inter-industry flow matrix describing the yearly economic transactions between supplying and receiving industries.

The Leontief inverse can be 'unraveled' through its power series expansion (Waugh, 1950), so that:

$$(I - A)^{-1} = I + A + A^2 + \cdots \qquad (2)$$

Equation 1 can be re-written as (Lenzen, 2007):

$$e_r = \sum_{i,j=1}^{n} s_{r,i} L_{ij} y_j \qquad (3)$$

Or

$$e_r = s_r (I - A)^{-1} y \qquad (3)$$

Where *i* and *j* are industry indices. Using the power series expansion in equation 2, equation 3 can be then decomposed as (Lenzen, 2007):

$$e_r = s_j(I + A + A^2 + \cdots)y = \sum_{i,j=1}^{n} s_{r,j} \left(\delta_{ji} + A_{ji} + \sum_{k=1}^{n} A_{kj} A_{ji} + \cdots \right) y_i$$

$$= \sum_{i=1}^{n} s_{r,i} y_i + \sum_{j=1}^{n} s_{r,j} \sum_{i=1}^{n} A_{ji} y_i + \sum_{k=1}^{n} s_{r,k} \sum_{j=1}^{n} A_{kj} \sum_{i=1}^{n} A_{ji} y_i + \cdots \qquad (4)$$

Where *i,j,k* are industry indices. The interpretation of equation 4 is as follows: the total resource requirement e_r is the sum over the direct resource requirements of industry *i* ($\sum_{i=1}^{n} s_{r,i} y_i$), plus the sum over first order paths from industry *j* to industry *i* ($\sum_{j=1}^{n} s_{r,j} \sum_{i=1}^{n} A_{ji} y_i$), plus second order paths from industry *k* via industry *j* into industry *i* ($\sum_{k=1}^{n} s_{r,k} \sum_{j=1}^{n} A_{kj} \sum_{i=1}^{n} A_{ji} y_i$), and so on. Thus, for a given industry *i* and resource *r*, the direct resource use corresponds to $s_{r,i} y_i$, while $s_{r,j} A_{ji} y_i$ corresponds to the indirect resource use along the path from industry *j* to industry *i* and $s_{r,k} A_{kj} A_{ji} y_i$ corresponds to the indirect resource use along the path from industry *k* via industry *j* to industry *i*. For any given industry, there are p paths of first order, p^2 paths of second order and, in general, p^P paths of P^{th} order. In practice, the exponential growth in the number of possible paths limits the amount of paths considered in an SPA owing to computational and time constraints (Sonis et al., 1997). It is thus common to limit the length of the paths as well as to apply a cut-off value indicating a minimum percentage of the total impact that a given node of the path contributes to (Peters and Hertwich, 2006). If the minimum contribution is not met, the evaluated node is excluded from the path and no further nodes are evaluated. Against this background, we limit the length of the paths to ten nodes, and apply a cut-off at 0.01%. Furthermore, there are various possible algorithms to operationalize an SPA (Lenzen, 2003), of which we apply an algorithm based on a dynamic tree data structure with tree pruning developed and documented by Peters and Hertwich (2006).

<heading level 2> SPA for the study of nexus issues

Decomposing the total resource use from the final demand of a given industry into unique pathways through SPA can offer valuable insights into nexus issues. Following our main research question, we focus on the relative importance of the various relationships between nodes leading to nexus problems. As described in Table 1, we focus on direct effects as well as dependent and interdependent relationships. In a first step, we obtain the most contributing paths for all *m* resources and for all *n* industries. This will yield $m \times n$ sets of paths. This step will provide information on the relative importance of the direct effects (paths of length 1) versus indirect effects (paths of length >1) of any given combination of industry and resource. For example, direct effects are likely to be important for industries characterized by the direct use of resources, such as extractive industries, while (inter)dependent paths may be important for industries that induce resource use mostly through their supply chains, such as service sectors. Furthermore, because some paths of length >1 will be excluded due to the imposition of a path length limit and/or a cut-off value, it is necessary to account for these in the form of a residual in order to fully decompose the total resource use. The residual is defined as:

$$residual_{r,i} = e_{r,i} - \sum_{q=1}^{p} SPA_{r,i} \quad (5)$$

Where *SPA* are the resource use values from each relevant path, *p* is the total amount of paths and *q* is an index of paths.

In a following step, we differentiate between paths of length >1 that describe dependent relationships and those that describe interdependent ones. To approach interdependencies, we assume that these take place in the form of feedback loops between pairs of industries and for pairs of resources. For example, a water-energy nexus in which energy use flows from an energy sector into a water sector and water use flows from a water sector into an energy sector. To identify such feedback loops, we evaluate all possible pairs of sets of paths of length >1 with differing starting nodes ($n_1 \neq n_2$) and differing resources analyzed ($r_1 \neq r_2$). A feedback loop will exist if both starting nodes are interconnected through paths of length >1. This will include direct paths between starting nodes (length 2) as well as paths with intermediate nodes (length >2). Both types of paths will be now labelled as pertaining to a feedback loop, and the rest will be assumed to be sequences of nodes or 'chains' describing only dependent relationships. It merits noting that such chains could include feedback loops if these are understood for a single resource, as circles of off-diagonal elements in A. Moreover, while it is possible that these chains contain other interdependent relationships not associated with the evaluated final node, these will be eventually captured, if relevant, in the corresponding pair of sets. The total resource use, for a given resource-industry combination, can thus be decomposed by aggregating the contribution of the paths according to the categories 'direct effect', 'feedback loop', 'chain' and 'residual'. We further differentiate between chains and feedback loops of length 2, 3 and more than 3 (+3).

Figure 2 presents a graphical example of the proposed two-step approach for industries n_1 and n_2 and resources r_1 and r_2. In this example, we first obtain four different sets of structural paths, where SPA (n_1,r_1) means an SPA performed to evaluate the total resource requirements of resource r_1 as a consequence of the final demand for industry n_1, and so on. In a second step, we identify which sets of paths describe feedback loops. In this case, SPA (n_1,r_1) and SPA (n_2,r_2) describe a feedback loop between industries n_1 and n_2. Theoretically, the remaining sets of paths could also describe feedback loops, since both the conditions $n_1 \neq n_2$ and $r_1 \neq r_2$ are also met, but we have excluded this possibility for simplicity. The path $s_{r_1,2}A_{2,3}A_{3,1}y_1$ describes a flow of resource r_1 from industry n_2 via industry n_3 into industry n_1, while the path $s_{r_2,1}A_{1,2}y_2$describes a flow of resource r_2 from industry n_1 into industry n_2. These two flows describe an interdependence between industries n_1 and n_2, and are therefore considered as pertaining to a feedback loop. A pseudocode describing the procedure to identify and classify feedback loops is presented in supporting information S3.

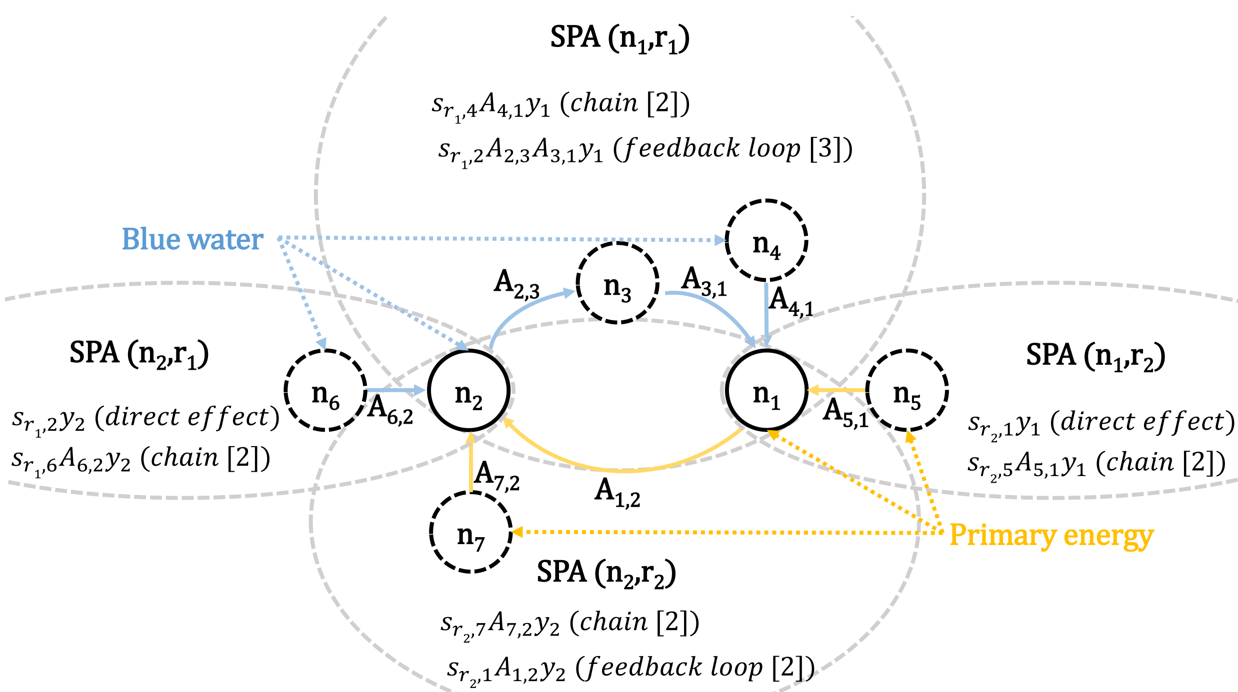


Figure 2. Example of the proposed approach to decompose total use of resources r_1 and r_2 caused by the final demand (y) of industries n_1 and n_2 into unique and categorized pathways. Solid arrows indicate monetary inter-industry dependencies, the color describes its associated resource flow, and dashed arrows indicate direct resource requirements. Solid and dashed circles indicate a final and an intermediate node, respectively. Numbers within square brackets indicate the length of the path. SPA stands for Structural Path analysis, s is the resource intensity and A are the technical coefficients.

<heading level 2> Case study design

The scope of our study is the global economy as defined by the MRIO database EXIOBASE v3.3 (Wood et al., 2014). It encompasses 44 of the largest world economies and 5 continent regions (Asia-Pacific, America, Europe, Africa, and Middle East) aggregating the rest of the world. Each of the countries/regions is described by 163 industries, making up a total economic resolution of 7,987 industries. For each industry, EXIOBASE v3.3 provides detailed environmental accounts for the years 1990 to 2015 (i.e. 40 emitted substances, 15 types of land use, freshwater withdrawals and consumption, and the consumption/use of various types of metallic and non-metallic minerals and biotic resources). It is important to note that the level of sectorial aggregation of IO data will influence the characteristics of nexus pathways, and so certain arbitrariness is introduced by selecting a specific MRIO database. That is, as individual industries are aggregated into industrial sectors, economic flows described by the MRIO database become less a product of actual interactions, and more the product of the aggregation itself. As an illustration, let us assume that industry A1 supplies to industry B1, and industries A2 and B2 do not interact. When industries A1, A2 and B1, B2 are aggregated respectively into sectors A and B, the interaction between sector A and B will be only true for industries A1 and B1. Consequently, relatively more aggregated IO data will misestimate to a larger extent both the resource use intensity and the inter-industry flows (de Koning et al., 2015), and in turn the relevant pathway characteristics such as path contribution to total resource use, path length and connectedness. Although EXIOBASE is one of the MRIO databases with most sector detail (Tukker et al., 2016), this issue will remain as long as any type of sectorial aggregation takes place.

Among the myriad of possibilities to study the resource nexus, this study focuses on the water-energy nexus caused by the final demand from the United States (US) and China. The year of study is 2007, as it is the base year for which most original IO tables were available. Energy use will be calculated through the use of primary energy carriers, while water use corresponds to blue water consumption. The final demand of each sector (y_i) used in the SPA will correspond to the total output delivered to the domestic final demand of each country. A detailed description of the economic sectors and resources included is presented in supporting information S1. Unraveling the water-energy nexus in the US and China constitutes a compelling case study. On the one hand, the water-energy nexus is one of the most relevant and well-studied nexus issues (Liu et al., 2015; Liao et al., 2016; Qin et al., 2015). Existing water-energy nexus studies focus mostly on interdependent (e.g. between regions, industries, factories, institutions, etc.) and sometimes complex (e.g. nonlinear) relationships (Liu et al., 2015). Since our approach is based on a linear model, nonlinear relationships are out of the scope of this study. By providing an economy-wide understanding of the relative importance of the direct and (inter)dependent relationships leading to the water-energy nexus, we are able to evaluate whether research efforts are appropriately allocated. On the other hand, US and China were among the largest economies and had distinct economic structures in the year 2007. The US was a diversified economy based largely on service-oriented sectors such as finance, while China was still transitioning from a manufacturing hub to a more consumer-oriented economy. Our study can also reveal the effects of such differences on the water-energy nexus.

<heading level 1> Results and discussion

This section is divided into two parts. The first part describes the water and energy pathways by industry, focusing on the relative importance of direct (based on direct effects) and indirect (based on both dependent and interdependent relationships) pathways. The second part focuses on analyzing the contribution of interdependencies or feedback loops to the water-energy nexus. For visualization and interpretation purposes, some results are presented according to broader industrial categories rather than individual sectors. The corresponding concordance can be found in supporting information S1. It merits to note that we speak of a water-energy nexus in those cases where both water and energy are used simultaneously, either directly or indirectly and irrespective of the absolute values of each resource. It is not the aim of this research to discuss the definition of the nexus itself (e.g. by defining a minimum threshold of resource use), but rather to explore the pathways leading to the combined use of resources.

<heading level 2> Nexus pathways

Our results indicate that, with the exception of some primary industries, such as agriculture, fuel extraction, and power generation, the water-energy nexus arises from resource use taking place upstream in the supply chains (indirect pathways) rather than on-site (direct pathways). This is illustrated by Figures 3 and 4, which show the contribution of both direct and indirect pathways leading to the water-energy nexus by industrial categories in the US and China. We find a generally consistent pattern across industries: pathways leading to the water-energy nexus become longer and more intertwined as supply chains grow in complexity. The water-energy nexus is often more evident in primary industries that require natural resources as factors of production, as resource use occurs on-site or in immediate suppliers. On the other hand, the water-energy nexus is less evident in manufacturing and service sectors, where most of the resource use takes place several steps upstream in their supply chain. This finding supports the conclusion of Li et al. (2012) and Okadera et al. (2015), who find supply chain effects to be important in the study of the water-energy nexus. In these cases, the residual accounts for a large share of the resource use, meaning that an important part of resource use is unknown as it takes place either in paths longer than ten steps and/or in multiple paths with little individual contribution (see section ‘Structural Path Analysis’). While the results are presented relative to the total, the absolute magnitude of each nexus can be weighted using the results in terms of absolute resource use that can be found in supporting information S2.

Disparities in the relative contribution of each type of pathway between the US and China can be largely explained by differences in economic structure, technology, resource endowments, or a combination of these. Such disparities are particularly evident in water pathways. For example, blue water consumption in the power generation by renewable energies sector in the US is dominated by the direct or on-site consumption, whereas this represents a small share in China. This is largely due to the relatively larger share of nuclear, biomass and geothermal in the US with respect to China, all of which have high direct requirements of blue water. Another example is the relatively larger contribution of direct water use in agriculture in the US with respect to China, which can be explained by the larger share of cattle farming, also a water-intensive activity. Moreover, manufacturing, transport and service sectors in China describe longer paths for blue water with respect to the US. This can be explained by the relatively more intensive use of fertilizer in China (Li et al., 2013), which creates relevant water pathways in the manufacturing of a variety of food and clothing products, as well as services.

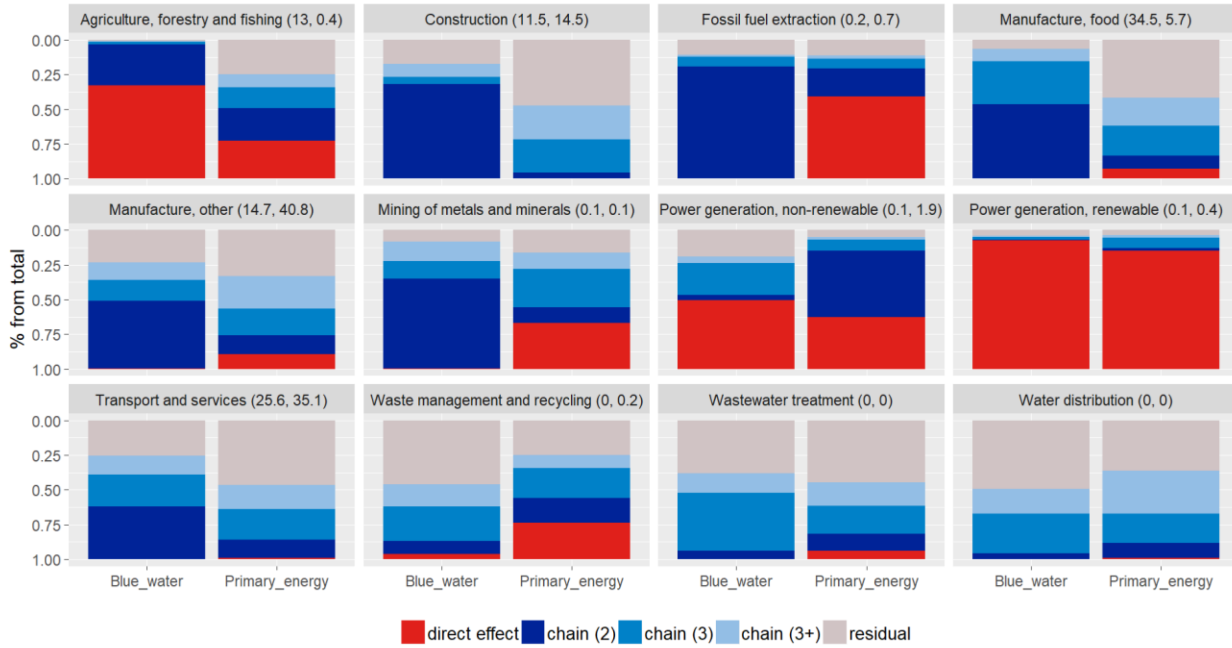


Figure 3. Contribution of direct and indirect blue water and primary energy requirements to total resource use by industrial categories in the United States. Within brackets, the contribution (in %) of blue water and primary energy sectorial use, respectively, from the total.

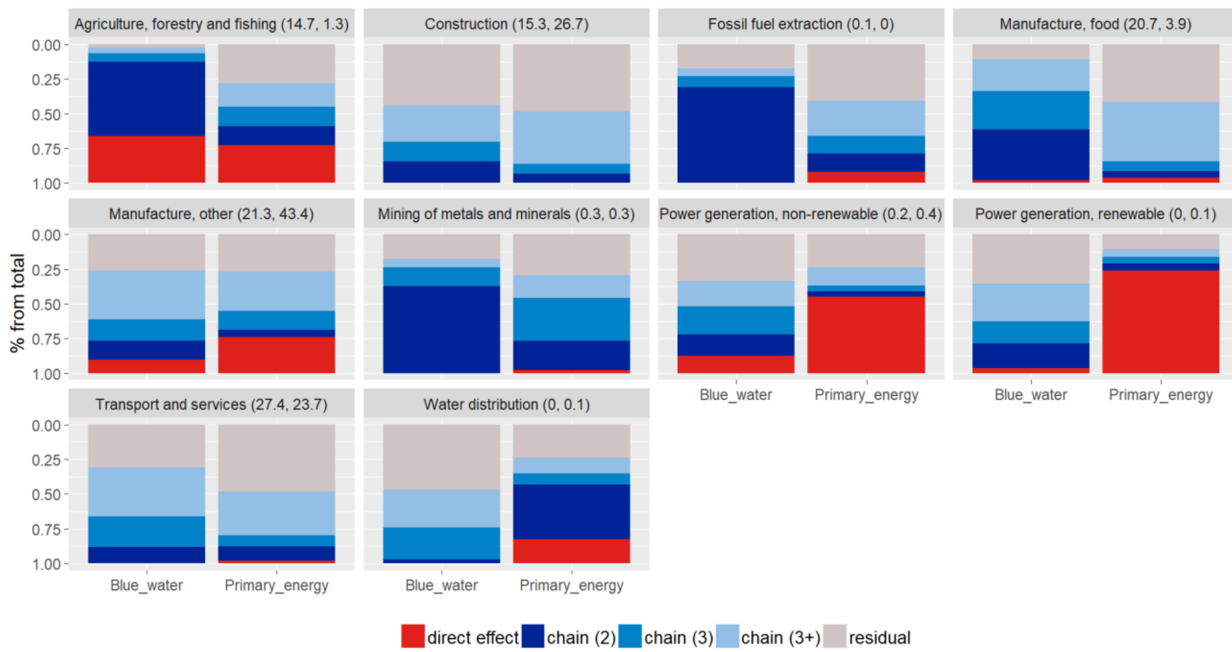


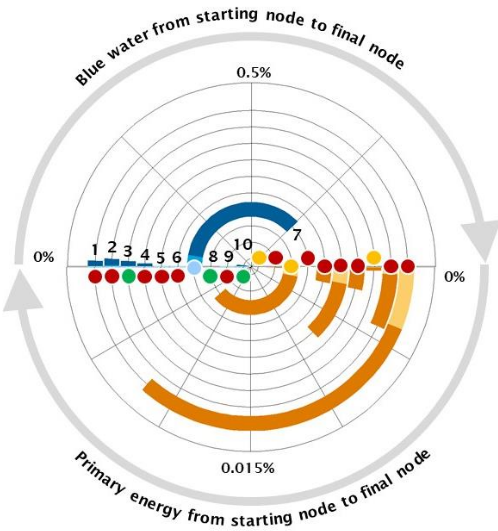
Figure 4. Contribution of direct and indirect blue water and primary energy requirements to total resource use by industrial categories in China. Within brackets, the contribution (in %) of blue water and primary energy sectorial use, respectively, from the total.

<heading level 2> Feedback loops

Our economy-wide analysis indicates the feedback relationships do not play an important role in the water-energy nexus for both the US and China. As illustrated by Figure 5, for any given combination of resource and industry pair, the most contributing feedback loops are found to account for less than 1% of total resource use. The most relevant feedback loops take place between sectors pertaining to the non-food manufacturing category, especially in China. The importance of this industrial category in terms of feedbacks can be explained by (1) the higher contribution of indirect water and energy pathways, (2) the size and number of pathways due to its economic size and (3) the higher interdependencies between individual sectors pertaining to this category. Another relevant finding is that feedback loops of length higher than two, thus involving one or more intermediate industries, play an important role. This is particularly true in the case of China and for energy pathways, with chemical sectors as important intermediaries. This demonstrates that the use of SPA allows for a more comprehensive study of the feedback loops leading to the water-energy nexus, as opposed to identifying two-way interdependencies directly in the IOTs.

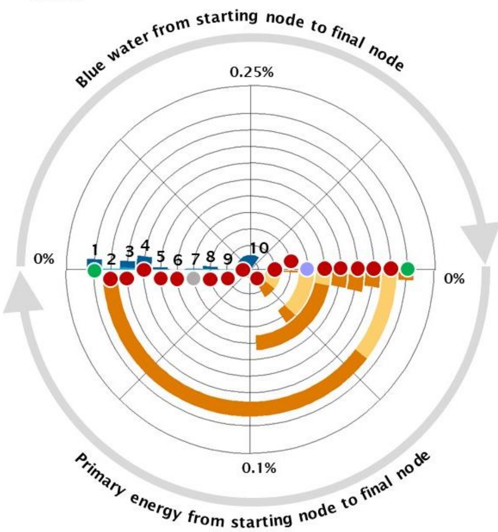
Strong feedback loops between industries are explained by a combination of relevant direct requirements of water and/or energy and strong economic interdependencies. The relative importance of each factor and the specific underlying reasons, however, will vary across individual feedback loops. For the US, the strongest feedback loops relate to the interdependencies between aluminum, iron and steel production and metal re-processing activities. These interdependencies are largely explained by the notable metal recycling levels in the US (Sibley, 2011). Specifically, metal producers supply 'new scrap' (e.g. cuttings and turnings) from metal fabrication and production processes to smelters and refineries, and the latter supply recycled metal to the former. For China, interdependencies between metal production and metal re-processing activities are also among the strongest, yet the most important feedback loop is between 'cultivation of paddy rice' and 'pigs farming'. In this case, rough rice, the cultivation of which requires of blue water, is included in pig diets (Wang et al., 2008), whereas pig manure, which requires primary energy to be produced (heating, ventilation, feed production, etc.), is used as fertilizer in rice fields.

United States



Pair number	Starting node (blue water)/ final node (primary energy)		Starting node (primary energy)/ final node (blue water)	
1		USA | Re-processing of secondary aluminium		USA | Aluminium production
2		USA | Aluminium production		USA | Re-processing of secondary aluminium
3		USA | Poultry farming		USA | Processing of meat poultry
4		USA | Re-processing of secondary steel into new steel		USA | Manufacture of basic iron and steel
5		USA | Re-processing of secondary plastic into new plastic		USA | Plastics, basic
6		USA | Manufacture of basic iron and steel		USA | Re-processing of secondary steel into new steel
7		USA | Production of electricity by tide, wave, ocean		USA | Chemicals nec
8		USA | Poultry farming		USA | Processing of Food products nec
9		USA | Manufacture of rubber and plastic products		USA | Plastics, basic
10		USA | Pigs farming		USA | Processing of Food products nec

China



Pair number	Starting node (blue water)/ final node (primary energy)		Starting node (primary energy)/ final node (blue water)	
1		CHN | Cultivation of paddy rice		CHN | Pigs farming
2		CHN | Lead, zinc and tin production		CHN | Re-processing of secondary lead into new lead
3		CHN | Manufacture of basic iron and steel		CHN | Manufacture of coke oven products
4		CHN | Manufacture of fabricated metal products		CHN | Manufacture of coke oven products
5		CHN | Re-processing of secondary lead into new lead		CHN | Lead, zinc and tin production
6		CHN | Re-processing of secondary steel into new steel		CHN | Manufacture of coke oven products
7		CHN | Extraction of natural gas		CHN | Steam and hot water supply
8		CHN | Re-processing of secondary aluminium into new aluminium		CHN | Aluminium production
9		CHN | Re-processing of secondary preciuos metals into new precious metals		CHN | Precious metals production
10		CHN | Precious metals production		CHN | Re-processing of secondary preciuos metals into new precious metals

Legend

Bars

feedback_loop (2) Blue_water; feedback_loop (3) Blue_water; feedback_loop (4+) Blue_water

feedback_loop (2) Primary_energy; feedback_loop (3) Primary_energy; feedback_loop (4+) Primary_energy

Dots/table

Fossil fuel extraction; Manufacture, other; Manufacture, food

Agriculture, forestry and fishing; Transport and services; Power generation, renewable

Figure 5. Contribution of the top feedback loops (as a percentage with respect to total 'known' resource use) for blue water and primary energy use and for pairs of industries in the United

States (top half) and China (bottom half). The colored dots inside the radial bar charts represent nodes or industries, with the color indicating the industry category. These industries act as starting (suppliers to other industries via inter-industry dependencies) or final nodes (suppliers to final demand), depending on whether water or energy flows are being evaluated. The top half of the chart depicts water flows from starting nodes (left side) to end nodes (right side), and the bottom half depicts the opposite directionality for energy flows. Each of the ten circular grid lines corresponds to a different feedback loop between a pair of industries. From the outer to the inner circles, feedback loops are ordered in decreasing order according to the geometric mean of the energy and water contributions. The value of each pathway corresponds to the contribution to the total 'known' resource use associated with the final node, that is, total use minus the residual. We exclude the residual in order not to underestimate the contribution of identified feedbacks, as additional feedbacks may be included in the residual. The path lengths are described within brackets.

Figure 6 presents an overview of all water-energy feedback loops by industry for the US and China. These results allow us to generalize some of the findings for pairs of industries previously discussed, and gain further insights into the weight and composition of feedback loops in the US and China. The aggregated results confirm the presence of stronger feedback loops in China, driven to a large extent by self-loops between non-food manufacturing industries. A number of reasons may be behind this trend, such as the overall lower energy efficiency levels (Andrews-Speed, 2009) and the larger role of water-intensive industries in China, such as chemical and textile manufacturing. In the US, feedback loops are overall largely driven by water flows from agricultural activities to manufacturing sectors, especially from cattle farming to meat production. Conversely, in China, feedback loops are overall driven by energy flows from manufacturing, transport, and services to fossil fuel extraction activities. Water-energy feedbacks involving non-renewable power generation and fossil fuel extraction are marginal in the US, but significant in China. The latter are largely driven by water and energy flowing from non-food manufacturing sectors (mostly due to machinery and plastic products), yet their counterparts are of little importance.

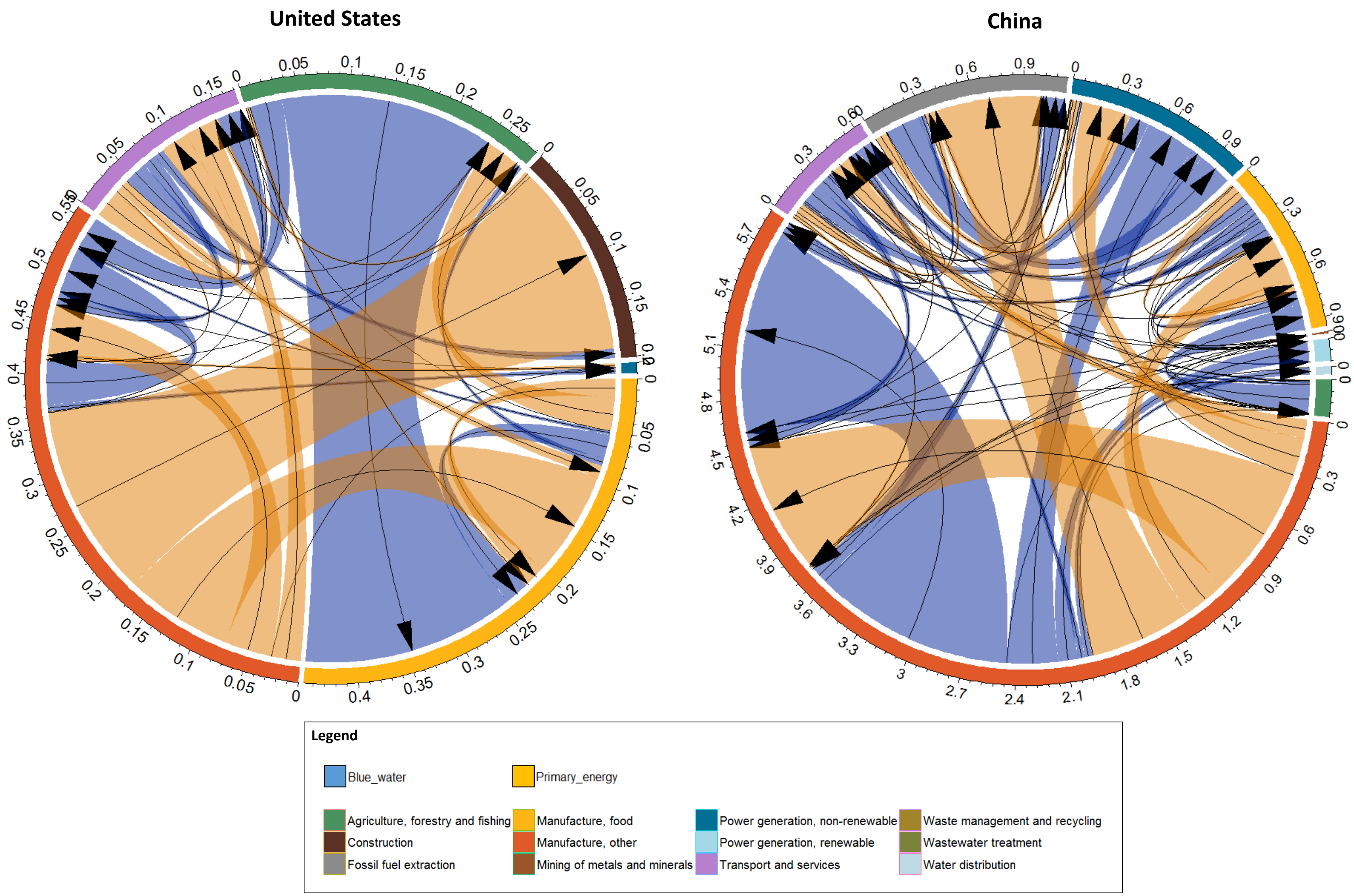

United States
China
Legend
Blue_water
Primary_energy
Agriculture, forestry and fishing
Construction
Fossil fuel extraction
Manufacture, food
Manufacture, other
Mining of metals and minerals
Power generation, non-renewable
Power generation, renewable
Transport and services
Waste management and recycling
Wastewater treatment
Water distribution

Figure 6. Feedback loops (as a percentage with respect to total 'known' resource use) among industrial categories in the United States (left) and China (right). Arrows indicate a water/energy flow from a starting node to a final node. The outer circular axis describes the contribution to total 'known' resource use. Each industrial category, represented by a different color, has its own axis starting at zero. From each industrial category, flows of water/energy, represented with an arrow and a different color, flow towards any given category, including the same where the flow originates. Each flow will have a counterpart flowing in the opposite direction for a different resource. The width of the flow represents the aggregated contribution of all individual inter-industry flows pertaining to a given category and flowing towards another given category. For example, a blue flow with a width of 1 flowing from A to B means that all the water pathways flowing from A contribute 1% to the total water use of B.

<heading level 1> Conclusions

In this research, we combine environmentally-extended multi-regional input-output analysis with structural path analysis (SPA) to quantify and compare the most relevant pathways leading to the resource nexus. Specifically, we approach pathways leading to the combined use of resources within economic systems, based on direct, dependent and interdependent relationships. For illustrative purposes, we apply this method to a comparative case study on the water-energy nexus in the United States (US) and China. Our approach differs from the mainstream resource nexus literature in that we first quantify the economy-wide use of two resources, and then trace back their individual pathways through supply chains to quantify and categorize them. This contrasts with more traditional case study-based approaches which identify specific (inter)dependencies (e.g. water consumption in an energy-intensive sector) in a given context of resource scarcity, supply risk, etc. The value of our approach is that it helps to better understand the pathways leading to the simultaneous use of two or more resources from any given sector. For instance, whether such pathways relate to the use of resources on-site, through supply-chain dependencies or via reinforcing feedback loops.

Our results indicate that (inter)dependent effects, where a water-energy nexus is generated through resource use upstream in the supply chain, are not only important but dominant in all industries apart from power generation. It is precisely these effects which input-output analysis is well suited to identify. Interdependencies or feedbacks have been claimed to be particularly important in the water-energy nexus, generally approached through the interaction between water and energy sectors (Bazilian et al., 2011; Hardy et al., 2012; Marsh, 2008). Our results indicate, however, that the water-energy nexus arising from economic activity does not originate so much from feedbacks but rather from dependent relationships and, to a lesser extent, direct resource use. Moreover, the most contributing water-energy feedbacks identified do not involve water nor energy sectors, but mostly manufacturing sectors. Feedbacks may still play a role in particular cases, but they appear to be of marginal importance when considering the economy as a whole. Further, feedbacks between specific agents can be exaggerated due to aggregation issues. This includes sectorial aggregation issues (de Koning et al., 2015; Su et al., 2010), but specially the abstraction of nexus problems by grouping multiple and heterogeneous agents into broad categories. For instance, the 'energy sector' could include individual industries related to fuel extraction, multiple generating technologies, distribution services, etc. This means that the actual feedbacks are likely to be even less determining. This finding calls into question current research efforts and suggests greater attention to less complex but more determining pathways leading to absolute resource use.

Our results can be useful in the design of resource management policies in both the US and China, as well as at other socio-economic contexts and at various scales. In the context of supply-chain dependencies, a possible application would be to guide consumer-oriented policies to target specific nexuses associated with final products in order to optimize trade-offs and co-benefits between water and energy. An example would be to promote vegetarian diets to mitigate the water-energy nexus (Marrin 2014). Another application of our approach would be to target key sectors through which water and energy propagate to final products, such as the propagation of both water and energy to agricultural final products through fertilizer production in China.

Potential actions involve shifting fertilizer types, crop species, and primary energy inputs (Foley et al., 2011). In the context of feedback loops leading to the water-energy nexus, our results indicate that policies aimed at enhancing virtuous circles or avoiding vicious circles by acting upon these feedbacks (Scott et al., 2015) should focus on manufacturing industries rather than water and energy sectors. However, given the modest importance of feedback loops according to our results, policies should rather focus on both on-site and dependent relationships.

The proposed SPA set-up entails computational limitations that hamper the full accounting of nexus pathways. This leads to large residuals that cluster unknown pathways, especially in sectors with complex supply chains such as manufacturing and service sectors. Considering that the largest share of final demand corresponds to these sectors, the intricacy of identifying specific pathways can hinder the effectiveness of consumer-oriented actions to mitigate the water-energy nexus. The development of more efficient SPA algorithms is thus a valuable research avenue. Furthermore, our study has focused on the resource nexus arising from economic relationships, and so other aspects commonly included in resource nexus studies, such as socio-political (e.g. trade policies) and biophysical processes (e.g. water cycles) (Andrews-Speed et al., 2014), have not been considered. It is thus plausible that more determining feedbacks are found when considering these aspects. Stronger feedbacks could also be found for other resources and regions/countries, as differences in the economic structure, technology levels and resource endowments play a major role. Further research is thus needed to confirm these hypotheses. Future efforts could greatly benefit from our approach, which has proven to be a productive undertaking by providing comprehensive information to identify and balance the pathways leading to the resource nexus.

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