Nexus strength: a novel metric for assessing the global resource nexus

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Summary

The limited access to natural resources is a major constraint for sustainability at various spatial scales. This challenge has sparked scholarly interest in the linkages or 'nexus' between resources, with a view to helping anticipate unforeseen consequences, identify trade-offs and co-benefits, and find optimal solutions. Yet despite decades of research, limitations in the scope and focus of studies remain. Recently constructed multiregional input-output (MRIO) databases, which cover the global economy and its use of resources in unprecedented detail, allow to systematically investigate resource use by production as well as consumption processes at various levels and garner new insights into global resource nexus (GRN) issues. This article addresses the question of how to prioritize such issues. Using the MRIO database EXIOBASE, we address the GRN considering five key resources: blue water, primary energy, land, metal ores, and minerals. We propose a metric of 'nexus strength', which relies on linear goal programming to rank industries and products based on its associated combined resource use and various weighting schemes. Our results validate current research efforts by identifying water, energy, and land as the strongest linkages globally and at all scales and, at the same time, lead to novel findings into the GRN, in that (1) it appears stronger and more complex from the consumption perspective, (2) metals and minerals emerge as critical yet undervalued components, and (3) it manifests with a considerable diversity across countries owing to differences in the economic structure, domestic policy, technology and resource endowments.

Keywords: resource nexus, footprints, input-output analysis (IOA), linear goal programming, resource management.

Graphical abstract

<heading level 1> Introduction

The limited access to crucial resources is increasingly perceived as a major constraint for environmental and economic sustainability (Graedel and van der Voet 2010; Liu et al. 2015). A number of technological systems, such as energy and food production, face challenges related to resource supply risk (Graedel et al. 2014; Graedel and van der Voet 2010). Some examples are the water constraints on electricity (Sovacool and Sovacool 2009) and food (Rijsberman 2006) production, as well as the scarcity of certain metals used for hydrogen fuel cells (Löschel et al. 2009) and photovoltaic technologies (Feltrin and Freundlich 2008). Such constraints are often related to political conflict, economic feasibility, institutional barriers as well as the physical availability of supporting natural resources (Andrews-Speed et al. 2012). In response to these challenges, the 'nexus framework' was proposed to aid resource management practices at meso- and macro scales (Liu et al. 2015).

The nexus framework focuses on the linkages between socio-ecological systems, and can help anticipate unforeseen consequences, identify trade-offs and co-benefits, and find optimal solutions between competing interests (Bizikova et al. 2013; Howells et al. 2013). When applied to natural resources alone, some authors speak of the 'resource nexus', and define it as the "linkages between different natural resources and raw materials that arise from economic, political, social, and natural processes" (Andrews-Speed et al. 2014). The (resource) nexus realm encompasses multiple focuses, such as competing use patterns, substitutability, and socio-political repercussions (Andrews-Speed et al. 2014). The nexus focus conceived here relates to the combined use of natural resources arising from economic processes, that is, the simultaneous use of two or more natural resources in productive activities or as a result of consumption. Following this approach, the goal of this article is twofold: (1) to identify key hotspots of combined resource use within the current global economic systems, and (2) to gain insight into the reasons behind the linkages between resources, namely co-occurrence, choice of technology, supply chain structure, etc.

<heading level 2> Current approaches to the resource nexus

Nexus studies generally deal with the (inter)dependencies between pre-defined nexus nodes (e.g. natural resources) and their related socio-economic agents (e.g. industries), usually through case studies. For example, when studying the water-energy nexus, the scope is typically to address the water used for energy production and/or the energy used for water supply in a particular case. Resource nexuses were initially approached during the 1980s in the form of food-energy nexus issues (Srilatha 1982), and such two-node patterns still dominate the literature. According to Liu et al. (2015), 80% of all nexus studies analyzed only two nodes, of which energy-water, food-water, and energy-food have been the most popular configurations. Additional nodes traditionally included in nexus studies are land use and greenhouse gas (GHG) emissions (Liu et al. 2015) . Most recently, there has been a great public and scholarly focus on the food-energy-water (FEW) nexus (Bazilian et al. 2011; Conway et al. 2015). The focus on a limited number of nodes can be justified by the *a priori* relevance of the selected nodes, the lack of data, as well as the aim to limit the complexity of the analyses. The consideration of additional supporting resources is however critical in some cases, as illustrated in the controversy surrounding biofuels. More specifically, the consideration of biofuels' GHG emissions from land use change, which was beyond the initial scope of the water-energy nexus, proved to be a key determinant of the overall carbon performance of biofuels (Plevin et al. 2010). Furthermore, material resources, such as metals and minerals, have not been the focus of nexus studies until recently (Graedel and van der Voet 2010; Graedel et al. 2014; Bekkers et al. 2014; Giurco et al. 2014), and there remains a lack of quantitative analyses to assess whether these are important nodes. The consideration of material resources as part of the nexus framework could unveil valuable insights, such as potential co-benefits from energy and water conservation and/or efficiency practices (Andrews-Speed et al. 2012). This resonates with complementary concepts such as circular economy, resource efficiency and industrial ecology (Clift and Druckman 2015).

Nexus issues have been studied at various geographical and economic levels, such as urban (Anu et al. 2017; Romero-Lankao et al. 2017; Kenway et al. 2011), regional (Lofman et al. 2002; Bartos and Chester 2014), and national levels (Kahrl and Roland-Holst 2008), yet the global scale remains largely unexplored. While some nexus issues are mostly location-dependent (e.g. water use from constrained reservoirs) (Bekkers et al. 2014), there is an explicitly global dimension to most nexus issues as local constraints can be mediated by trade, as illustrated by virtual water trade (Allan 1998; Wang and Zimmerman 2016) and land use displacement (Meyfroidt et al. 2010; Weinzettel et al. 2013). Moreover, most of the nexus literature focuses on particular industries, such as food and energy, where large quantities of natural resources are directly used. In consequence, those industries with no immediate resource implications or in which resource interdependencies reside across the ever more complicated and global supply chains are overlooked. For instance, service-based industries such as construction, can indirectly induce considerable resource use (electricity production, metal products, etc.). Comprehensive analyses across the whole economy thus have the ability to identify previously unnoticed nexus issues. Against this background, three research avenues present unexplored potential: (1) the simultaneous study of multiple natural resources — including material resources— as nexus nodes, (2) the study of nexus issues at the global scale, and (3) the inclusion of all economic agents as mediators of nexus issues.

<heading level 2> The resource nexus and input-output economics

Input-output analysis (IOA) in combination with recently constructed global multi-regional input-output (MRIO) databases (Leontief 1970; Miller and Blair 2009; Tukker and Dietzenbacher 2013), with their global and comprehensive coverage of industry interdependencies and resource use, can offer new insights into the global resource nexus (GRN) while addressing the above research gaps in a consistent way. These databases describe inter-industry relationships within national economies and through international trade, and are being developed with an increasing sectoral detail and representation of environmental pressures (including material resource use) (Tukker and Dietzenbacher 2013; Wiedmann et al. 2011). These databases allow to study GRN issues for all industries and multiple resources, as well as to gain insight into their economic drivers from both a production and consumption perspective. It is thus possible to consistently account for the technological requirements (direct use) and the economic dependencies (indirect use), which together contribute to the associated resource use of any industry or product.

Interdependencies, a core focus of nexus studies, are implicit in accounting for indirect resource use (e.g. water use will be allocated to electricity sectors, and vice versa for energy, through upstream dependencies). While prior sector- and location- specific nexus studies offer detailed insights into specific (inter)dependencies, the IOA approach enables a comprehensive picture of integrated natural resource use and hotspots across all industries worldwide.

The strengths of IOA for the study of nexus issues, however, may come at the price of aggregation over individual processes and spatial scale (Suh 2009). IOA-based approaches will thus offer a complement to rather than a replacement of traditionally more case-study focused nexus studies. The lack of global, system-wide relevant data, such as market prices and certain environmental accounts (e.g. minor metals) is another constraint, yet recent developments in terms of increased geographical coverage (Lenzen et al. 2014) and environmental accounts (Wood et al. 2014) are expected to progressively facilitate such integration. Notwithstanding the limitations, resource nexus problems are in the present and the future research agenda of the IO community (Dietzenbacher et al. 2013).

Pioneering works on the interplay between the nexus framework and IOA addressed the water-energy nexus through case studies. Among these, Marsh (2008) suggested various IO techniques to address multiple dimensions of nexus issues (linkage analysis, dependency analysis, multiplier analysis and scenario analysis), while Kahrl and Roland-Holst (2008) identified three relevant metrics to quantify the nexus: physical, monetary and distributive. These early studies highlighted the limited representation of capital stocks as well as the resolution and static nature of IO tables as shortcomings, and these were later dealt with to some extent by integrating process-based life cycle data in the form of hybrid IO models (Mo et al. 2014; Gu et al. 2014; Li et al. 2012; Wu and Chen 2017). Other authors highlighted the inattention to local conditions (e.g. resource scarcity and quality) caused by the limited spatial resolution of IO tables, and proposed the use of stress-based indexes (Feng et al. 2014) and subnational IO tables (Okadera et al. 2015). More recently, and in the context of the increasing importance of interregional and international trade, nexus studies applied MRIO (Miller and Blair 2009; Duchin and Steenge 1999) and ecological network analysis (ENA) (Fath and Patten 1999) to explore structural properties and sectorial interactions of extended economic systems (Guo and Shen 2015; Wang and Chen 2016; Duan and Chen 2017; White et al. 2017; Yan and Ge 2017).

<heading level 2> Resource nexus metrics

While the use of MRIO databases can offer valuable insights into the GRN, the increased scope in terms of resource, geographical, and economic representation presents the challenge of identifying which specific nexuses merit attention. In this sense, the development of performance metrics becomes essential to prioritize among the multiple possible alternatives and in light of conflicting interests (Andrews-Speed et al. 2014). A number of performance indicators have been used to study nexus issues, such as the 'energy intensity of water use' (Kahrl and Roland-Holst 2008), the 'energy return on water invested' (Voinov and Cardwell 2009) and systems-based indicators (e.g. betweenness (Zimmerman et al. 2016) and dependence coefficients (Wang and Chen 2016)). However, no existing quantitative metric is readily suitable to compare resource nexuses involving multiple resources and sectors/regions simultaneously.

A key research question is thus: How can the most challenging resource nexus issues from global economic processes be identified?

In this article, we develop a quantitative metric for the study of the GRN based on MRIO data. We apply this metric to compare and rank resource nexus issues arising from global economic processes related to both production and consumption. This metric, which we label as 'nexus strength', aims to identifying the most significant resource nexuses based on the simultaneous absolute use of natural resources. That is, which resource nexuses of a product, an industry, a country, or the world, contribute more to global natural resource usage? We aim to develop a simple indicator that is both meaningful and easy to understand, yet flexible enough to incorporate key issues for the nexus such as resource scarcity and quality, substitutability and/or economic value, among others. This paper is expected to contribute to the current understanding and managing of nexus issues mainly in two ways. First, the use of MRIO with state-of-the-art environmental extensions allows to investigate potentially overlooked nexuses as well as associated synergies and co-benefits. Second, a performance metric would allow users to identify the most challenging nexuses, potentially guiding more detailed analyses at finer sectorial and spatial scales.

<heading level 1> Methods and data sources

This section first presents the scope of the study in terms of temporal and spatial boundaries, accounting approaches and indicators used, as well as the sources of data. Following is presented a method for multi-regional input-output analysis (MRIOA) for both production and consumption perspectives. The formulation of a performance indicator to identify and rank nexuses, labelled as ‘nexus strength’, concludes this section.

<heading level 2> Scope and sources of data

The scope of this study is the global economy, represented by the MRIO database EXIOBASE v3.3 (Wood et al. 2014). For the years 1995-2014, EXIOBASE v3.3 contains all monetary transactions between 163 industries and final users across 49 regions (44 of the largest world economies and 5 continent regions aggregating the rest of the world). Thus, 7,987 (i.e. 49×163) country-specific industries specifies the global economy each year. EXIOBASE v3.3 also contains multiple environmental accounts (direct resource use and emissions) in physical units at the same industry and country detail and time resolution. Focusing on the impacts of natural resource extraction, this study considers five critical nodes of the GRN: use of primary energy carriers (referred to as just ‘energy’), consumption of blue water (fresh surface and groundwater) (‘water’), use of (arable) land (‘land’), domestic extraction used of metal ores (‘metals’) and domestic extraction used of non-metallic minerals (‘minerals’). These resources, especially the first three, have been a popular focus of the nexus literature (Andrews-Speed et al. 2014; Liu et al. 2015; Graedel and van der Voet 2010), yet rarely assessed simultaneously. It merits noting that the chosen nexus nodes have a heterogeneous composition (e.g., ‘metals’ include multiple types of ores), yet have been aggregated to make the analysis more concise and interpretable. For the same reasons, and when possible, we have selected broad categories as a proxy of more detailed resources, such as land use as a proxy of various types of biomass (crops, timber, fish products, etc.) and primary energy as a proxy of various energy carriers (fossil fuels, uranium, waste, etc.). We have also excluded food, a common nexus node, as it is generally an economic product rather than a natural resource. We have chosen the year 2007 as it is the reference year for which the highest quality data is available. A detailed description of the regions, industries and resources included in this study is presented in supporting information S1.

For the main analysis, we analyze the GRN from the two main accounting perspectives in IOA, namely the production-based accounting (PBA) and the consumption-based accounting (CBA

). When following the PBA, we speak of an industry nexus, whereas, when following the CBA, we speak of a product nexus. The PBA is based on the territorial-based approach (IPCC 1996) and includes all resource use taking place within given political boundaries. Resource use of an industry thus corresponds to its direct resource extractions, commonly from within a local/regional territory, used as factors of production. The CBA emerged with the aim to account for the driving forces for resource use associated with consumption (Eder and Narodoslawsky 1999; Tukker et al. 2014; Hertwich and Peters 2009; Wiedmann et al. 2015). In this case, the resource use corresponds to all resources used along the supply chains, i.e. both direct and indirect resource use, that contributes to the provision of a finished product or service for final consumption. The MRIO database further enables tracing resource use throughout global supply chain to the final consumption in individual nations. As such, PBA and CBA offer complementary insights into the GRN. The PBA captures actors that directly extract and use multiple natural resources, and so nexuses relate mostly to technology requirements (e.g. land, minerals, and water to produce food). On the other hand, the CBA traces direct resource use along supply chains to final consumers of goods and services, illuminating the ultimate drivers of the nexus and the resource (inter)dependencies (e.g. energy to deliver drinking water) essential to realize the ultimate human needs. To account for the overall effect of an industry rather than its direct contribution or the effect attributable to final demand, alternative approaches, such as the total flow concept (TFC) (Szyrmer 1992; Jeong 1984), have been proposed. The TFC can be understood as a production-based footprint, as it estimates the direct plus indirect inputs associated with each industry's output. Although its use for impact analysis suffers from non-additivity (Milana 1985; Gallego and Lenzen 2005) (indirect inputs are systematically double-counted), we replicate our proposed approach with the TFC for the purpose of discussing its potential value for the study of the resource nexus. We provide a detailed description of the TFC calculations in supporting information S2.

<heading level 2> Input-output analysis

In a first step, we calculate the resource use associated either with each country-specific industry (just 'industry' from hereon) (PBA approach or industry nexus) or with the final demand of finished product from each industry (CBA approach or product nexus). This information is then used to build an indicator of 'nexus strength'. Direct resource use is readily available in EXIOBASE v3.3 in the form of environmental extensions, and so a vector of direct use of resource *r* (e.g.

primary energy) by industry *i* ($e_{r,i}^{PP}$) can be calculated by aggregating all the rows corresponding to individual resources (coking coal, gas coke, etc.) that pertain to a given resource, as:

$$e_{r,i}^{PP} = \sum_{k=1}^{h} F_{\cdot i} \quad (Eq.1)$$

Where *F* is an *m* x *n* resource use matrix indicating the amount of each resource *r* used by each industry *i*, *m* and *n* are the number of resources and industries, respectively, *k* is an index of component resources summarized by *r*, and *h* is the number of component resources (see supporting information S1 for a complete list of resources).

The total use of resource *r* associated with the final demand for the product of a given industry *i* ($e_{r,i}^{CP}$) is calculated through Eqs. 2-3. Briefly, based on the Leontief model (Leontief 1970) (Eq. 3), inter-industry input-output matrices (*A*) are used to calculate the total output (direct plus indirect, *x*) required to satisfy a given final demand (*y*). In our case, *y* corresponds to the total final demand (for all final demand categories) for a given industry *i*, so a vector of zeroes where the entry for industry *i* corresponds to the total output delivered by this industry to the various final demand categories (households, capital formation, etc.). Using the unit environmental pressures associated with the output of each industry (*s*), the environmental repercussions of such final demand can then be calculated, an approach known as environmentally-extended IOA (Miller and Blair 2009).

$$e_{r,i}^{CP} = s_r x; \quad (Eq. 2)$$

$$x = (I - A)^{-1} y = Ly; \quad (Eq. 3)$$

Where *A* is an *n x n* matrix of technical coefficients indicating the inter-industry inputs required to supply one unit of output, *I* is an *n x n* identity matrix, *L is* the Leontief inverse containing the multipliers for the direct plus indirect inter-industry inputs required to satisfy one unit of final demand, *y* is a given *n* x 1 final demand vector, *x* is the resulting monetary output vector to satisfy *y*, and s_r is a 1 x *n* resource intensity vector indicating the resource use per unit of output by industry.

For the CBA approach, the indirect resource use (ei^{CP}), or the resource use associated with the output of industry *i* to final demand, can be calculated by subtracting *y* from *x*, so that (Oosterhaven 1981):

$$ei_{r,i}^{CP} = s_r x^*$$

$$with\, x^* = x - y \quad (Eq. 4)$$

Consequently, direct resource use associated with the output of industry *i* to final demand (*ed*) can be calculated as:

$$ed_{r,i}^{CP} = e_{r,i}^{CP} - ei_{r,i}^{CP} \quad (Eq. 5)$$

While $ed_{r,i}^{CP}$ corresponds to the resources used directly by a industry *i* to deliver own outputs to final demand, direct resource use of industry *i* ($e_{r,i}^{PP}$, see equation 1) corresponds to the total resources used by industry *i* that are associated with the whole economy's final demand (own plus other industries' outputs).

<heading level 2> Nexus strength

Using the equations presented in the previous section, resource use associated with any given industry or product is calculated for all five selected resources. In the context of the study of resource nexus issues, this presents two challenges. First, how do we define a resource nexus? And second, how can we identify the most relevant or 'stronger' nexuses if each resource has different units? Mathematically, the first issue involves a normative decision on the minimum number of resources that constitute a nexus, as well as regarding a given threshold that determines the minimum use that will be tolerated for a nexus to take place. For example, if a given industry uses a significant quantity of water and a marginal amount of energy, one can call into question whether it constitutes a water-energy nexus. The second issue is commonly associated with the concept of environmental multi-dimensionality or incommensurability (Funtowicz et al. 1999). As an example, let us assume that industry A uses 10 units of water and 5 units of energy, whereas industry B uses 5 units of water and 10 units of energy. When evaluating which industry presents the most challenging nexus, the result will depend on how the importance of each resource is weighted (based on relative use, scarcity, price, etc.). In this analysis, we address both issues through linear goal programming (LGP), a type of multi-objective optimization model within the umbrella of multi-criteria decision analysis (Ignizio 1985). LGP can be used straightforwardly to study multiple environmental issues within the Leontief model (Miller and Blair 2009).

An LGP set-up follows the basic structure of linear programming, that is, an objective function (Eq. 7) that is optimized following a set of constraints (Eqs. 8-14). LGP deals with the issue of multi-dimensionality by calculating unitless deviations from pre-defined goals. These deviations are then optimized, i.e., minimized or maximized, in the objective function. In our case, we set the goals, for each resource analyzed, as the macroeconomic (for all industries) or the sector (for all industries of the same type) maximum resource use, respectively (Eq. 9-13). The goal thus acts as an undesired reference. The deviation represents the ratio of the use of a resource by a given industry to the use of the same resource by the industry having the highest resource use at the macroeconomic/sector level. In order to find the most resource-intensive industry, we define a maximization objective function (Eq. 7). It is common to weight the deviations of different resources, possibly with some constraint setup (Eq. 8), to reflect their relative importance. The imposition of other constraints allows for dealing with the issue of the nexus definition, as a set of constraints can ensure both a minimum number of different resources and a minimum quantity of each resource use. In our case (Eq. 14), we set a minimum of two resources and a minimum relative deviation (as a proxy of resource use) of 1% (i.e. h=1%). That is, for any given combination of at least two resouces, the highest deviation among all resources used is taken as a reference, and any other deviation must be no less than 1% or otherwise it is excluded from the combination. This threshold ensures that a given nexus is not composed of any resource with a trivial use. We label the result of the objective function as the 'nexus strength' of a particular industry or product. In turn, each single deviation can be understood as the contribution of each resource to the nexus strength. The nexus strength metric ranges from 1 (maximum use for all resources) to 0 (no use of resources). By iterating the proposed LGP approach a given number of times, we can calculate which industries have the highest nexus strength. Differently from a simple ranking procedure, linear programming approaches are much more efficient in finding optimal solutions, as all possible combinations need not to be evaluated thanks to the use of constraints. Mathematically, the LGP approach to find the strongest nexus can be formulated as follows:

$$Maximize: \quad nexus\ strength_i = p_w d_{w,i} + p_e d_{e,i} + p_l d_{l,i} + p_m d_{me,i} + p_r d_{mi,i} \quad (Eq. 7)$$

$$with\ i \in I\ ; I = \{1, \dots, n\}$$

$Subject\ to$:

$$\sum_{R}^{n} (p_n) = 1\ ; R = \{w, e, l, me, mi\} \quad (Eq. 8)$$

$$d_{w,i} = \frac{e_{w,i}^{PP|CP}}{g_w}\ ;\ g_w = \max(\{e_{w,i}^{PP|CP}\})_{i \in I|J} \quad (Eq. 9)$$

$$d_{e,i} = \frac{e_{e,i}^{PP|CP}}{g_e}\ ;\ g_e = \max(\{e_{e,i}^{PP|CP}\})_{i \in I|J} \quad (Eq. 10)$$

$$d_{l,i} = \frac{e_{l,i}^{PP|CP}}{g_l} \; ; \; g_l = \max(\{e_{l,i}^{PP|CP}\})_{i \in I|J} \;\; (Eq. 11)$$

$$d_{m,i} = \frac{e_{me,i}^{PP|CP}}{g_{me}} \; ; \; g_{me} = \max(\{e_{me,i}^{PP|CP}\})_{i \in I|J} \;\; (Eq. 12)$$

$$d_{r,i} = \frac{e_{mi,i}^{PP|CP}}{g_{mi}} \; ; \; g_{mi} = \max(\{e_{mi,i}^{PP|CP}\})_{i \in I|J} \;\; (Eq. 13)$$

$$with\, J = \{1, \dots, z\}$$

$$d_{q,i} \geq d_{c,i} h \quad (Eq. 14)$$

$$with\, q, c \in N \; ; \; q \neq c \; ; \; d_{c,i} = \max\left(\{d_{v,i}\}\right)_{v \in N}$$

Where d_i is the deviation from the goal of the *i*th industry in the form of a coefficient, *p* is a weight that determines the relative importance of a given resource in the objective function (in our case, we apply equal weights [0.2]), I is an index of all industries of the global economy (used to determine macroeconomic maxima), *J* is an index of all industries across countries pertaining to the same industry type as industry *i* (used to determine sector maxima), *z* is the number of unique sectors, *w, e, l, me* and *mi* stand for water, energy, land, metals and minerals, respectively, and *g* is the goal to be achieved for each resource, in this case corresponding to the macroeconomic or sector maximum resource use. In order to ensure that at least two resources have a significant use, a threshold *h* is used to indicate the minimum percentage of resource *c* that a given resource *q* (any other than *c*) must satisfy, *c* being the resource with the largest deviation for the *i*th sector.

While simple in its formulation, our LGP approach is flexible to be expanded in multiple ways that are relevant for the study of the resource nexus. Such expansions can be included via the weightings, the goal definition or the constraints in a given LGP set-up, depending on the specific case. For example, the goals could be defined based on alternative criteria, such as resource availability, economic feasibility, policy targets, and/or planetary boundaries. The goals could also differ among countries and/or industries if desired. Alternative weightings can also be applied, and, to illustrate this, we use the following weightings as suggested by Oers and Tukker (2016): (1) ‘panel data’: according to expert judgment; (2) ‘distance-to-target’: deviations from 2050 world boundaries; and (3) ‘shadow prices’: non-market prices (further information on the weightings is available in supporting formation S3). Other nexus aspects that can be included in optimization models are competing interests within environmental constraints (Leavesley et al. 1996), as well as technical, capital capacity and demand limits (Zhang and Vesselinov 2016). The proposed nexus strength metric provides a simple representation of the relevant resource nexuses in the scope of the global economy. The practical relevance of this metric will however depend on specific local environmental, socio-economic and political conditions.

<heading level 1> Results

This section presents the GRN results according to the proposed nexus strength metric and for the five selected resources: water, energy, land, metals and minerals. The main results have been calculated using equal weights (each resource receives the same importance), and so the nexus strength will relate solely to the absolute resource use. Also, the deviations have been calculated with respect to macroeconomic maxima (among all world industries). We thus speak of a strong nexus when the simultaneous use of at least two resources is significant with respect to the macroeconomic maximum resource use. Additional results using sector maxima, different weighting schemes (‘distance-to-target’,’ panel data’, and ’shadow prices’), sensitivity of the threshold *h*, and normalized resource use (according to industrial output) are used for discussion purposes and can be found in supporting information S3 and S4. First, an overview of the GRN is presented. Then, at the industry level, the results from both the production perspective (i.e. nexus strength associated with each industry’s production activity) and the consumption perspective (i.e. nexus strength caused by the final demand for each industry) are analyzed. Lastly, we present the country-level nexus strengths from the production perspective.

<heading level 2> Global overview of the nexus strength

An overview of the resource nexus for the global economy, corresponding to the aggregation of the nexus strength values of each country-specific industry (see equation 7), is presented in Figure 1. It merits noting that relatively more frequent resources (those which appear in a larger amount of nexus) will be overrepresented as all possible two-node combinations are considered, and so the individual contribution of each resource will be included in each combination. For example, a water-energy-land nexus will be broken into all possible two-node combinations: water-energy, water-land, and energy-land. If, let us assume, water has a high nexus strength, such strength will propagate to all water nexuses: water-energy and water-land. The proposed visualization should thus be interpreted as a measure of the importance of two-node linkages, representing both the nexus strength and the frequency of the resources. For a measure of the nexus strength alone, we refer to the industry and product-level results presented later on this section. The visualization of the results is similar to the representation of relationships between resources by Andrews-Speed et al. (2014), yet instead of inputs and substitution possibilities, the edges and vertices (nodes connected by edges, as per graph theory) indicate the nexus strength.

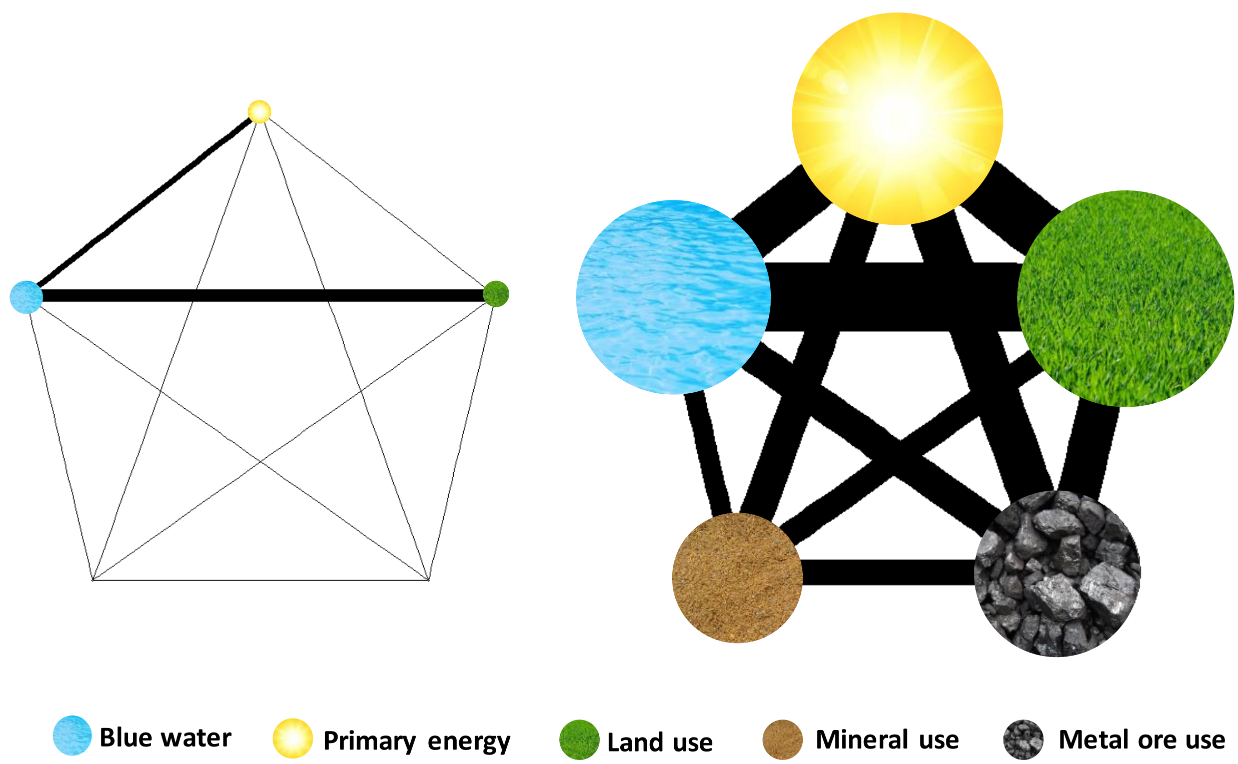

Figure 1. Overview of the global resource nexus from a production perspective (left side) and a consumption perspective (right side). Edges indicate the aggregated contribution of any given combination of two resources (for nexuses of more than two resources, all possible pairs are included), while vertices indicate the aggregated contribution of a given resource. A strong nexus

between two resources, represented by a relatively wider edge, means that these resources are used simultaneously in large quantities across the global economy.

For industry nexuses (PBA or production perspective), we find important water-land and water-energy nexuses. The same combinations are important for product nexuses (CBA or consumption perspective), in addition to the energy-land and energy-metal ones. There is, however, a striking difference of the GRN strengths when viewed from the two perspectives – the strengths of the two-node nexuses appears much stronger for product nexuses. A plausible explanation relates to the threshold applied in the definition of the nexus. From a production perspective, primary and secondary industries are main users of natural resources across the world, and in many cases, a given industry has such a dominant role in the usage of a single resource that its usage of other resources become insignificant (i.e. below the h threshold in Eq. 14). For example, mining industries dominate the direct usage of metals or mineral ores across all economic activities. Their usage of other resources such as water and primary energy, however considerable in absolute values, become much less relevant concerning global resource security. Many resources thus fall below the proposed threshold of 1%, and the resource and/or the industry are excluded from the analysis as no nexus is identified. This hypothesis is confirmed by the fact that, when the threshold is lowered, the number of industries for which a nexus is identified increases more rapidly for industry nexuses than the product nexuses. For instance, a threshold of 1% yields a count of 3875 and 6660 nexuses according to the PBA and CBA approaches, respectively, whereas a value of 0.1% yields a count of 4580 (18% increase) and 6777 (2% increase), respectively. A more detailed look (see Figure S4.4 in supporting information S4) reveals that, for PBA nexuses, changing the threshold affects mostly mining industries, although this change does not significantly alter the global nexus strength nor the role of neither minerals nor metals (see Figure S4.6). Moreover, product nexuses are made up by a larger amount of resources, and so the double-counting caused by considering any possible pair of resources will play a bigger role. The higher two-node nexus strengths measured for product nexuses also reflect complex networks involving multiple resources along supply chains of the finished products ultimately consumed. As such, our results indicate that the resource use and security concerns arising from the nexus are more crucial from a consumption perspective, i.e. the GRN is more critical regarding the provision of finished products and services than the production activities in general.

<heading level 2> Industry and product-level nexus strength

Following, the top 25 industry and product nexuses are presented in Figures 2 and 3, respectively. For industry nexuses, water-land and water-energy remain the strongest combinations. Among all the identified nexuses, energy (E) and water (W) are the most frequent nodes (present in 94% and 92% of nexuses, respectively), followed by land (L, 32%), minerals (Mi, 22%) and metals (Me, 9%). This pattern suggests that the direct use of land, minerals, and metals are relatively concentrated while the consumption of primary energy and blue water are widely distributed across the industries. Out of a total of 22 configurations of at least two nodes identified, the most frequent configurations are W+E (50%) and W+E+L (18%). These results suggest that the current focus of the nexus research on combinations of water, energy and land (Bazilian et al. 2011), are aligned with the most frequent combined direct resource use we identified in the context global economy.

In contrast to the industry nexuses, product nexuses are more complex and involve multiple nodes, such as the water-energy-land-metal-mineral and water-energy-land nexus (Figure 3). Among all the identified nexuses, E and L are the most frequent nodes (both present in 98% of nexuses), followed by W (96%), Me (94%), and Mi (89%). Out of a total of 23 configurations of at least two nodes, the most frequent combinations are W+E+L+Me+Mi (86%) and W+E+L+Me (5%). Also in contrast to the industry nexuses, we observe strong W+E nexuses, largely due to the role of coal electricity in supply chains in USA and China. Also, the strength of water nodes decreases with respect to industry nexuses, as its use, mostly focused in cultivation, is spread along supply chains (e.g., food services and biofuels). On the other hand, land nodes remain relatively stronger as its use remains concentrated in shorter supply chains of meat products.

The top product nexuses are largely attributable to indirect resource use. The main reason is that final demand is generally higher for service-based activities (e.g. retail) than primary (e.g. farming) and secondary (e.g. meat production) activities, and the former use relatively less resources directly as factors of production. The assessment of metals and minerals is relatively unexplored in nexus studies, and the same is true for service-based industries such as construction and public administration. Our results suggest, however, that these resources and industries play a more important role than previously thought in the resource nexus. Compared with their industry counterparts, product nexuses present higher nexus strength values, which suggests that nexus issues may be minimized more effectively and in a more comprehensive manner by targeting final demand categories.

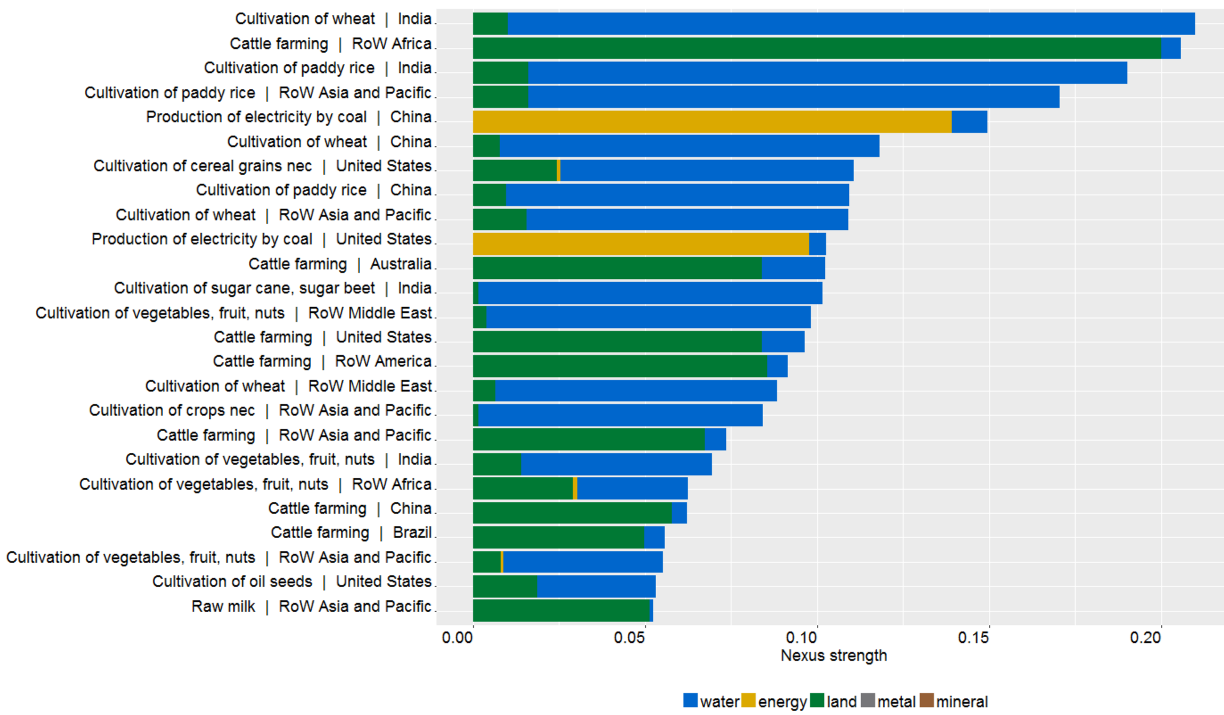

Figure 2. Nexus strength (with contribution by resource) of the top 25 industry nexus identified through production-baed accounting. RoW: rest-of-the-world; nec: not elsewhere classified.

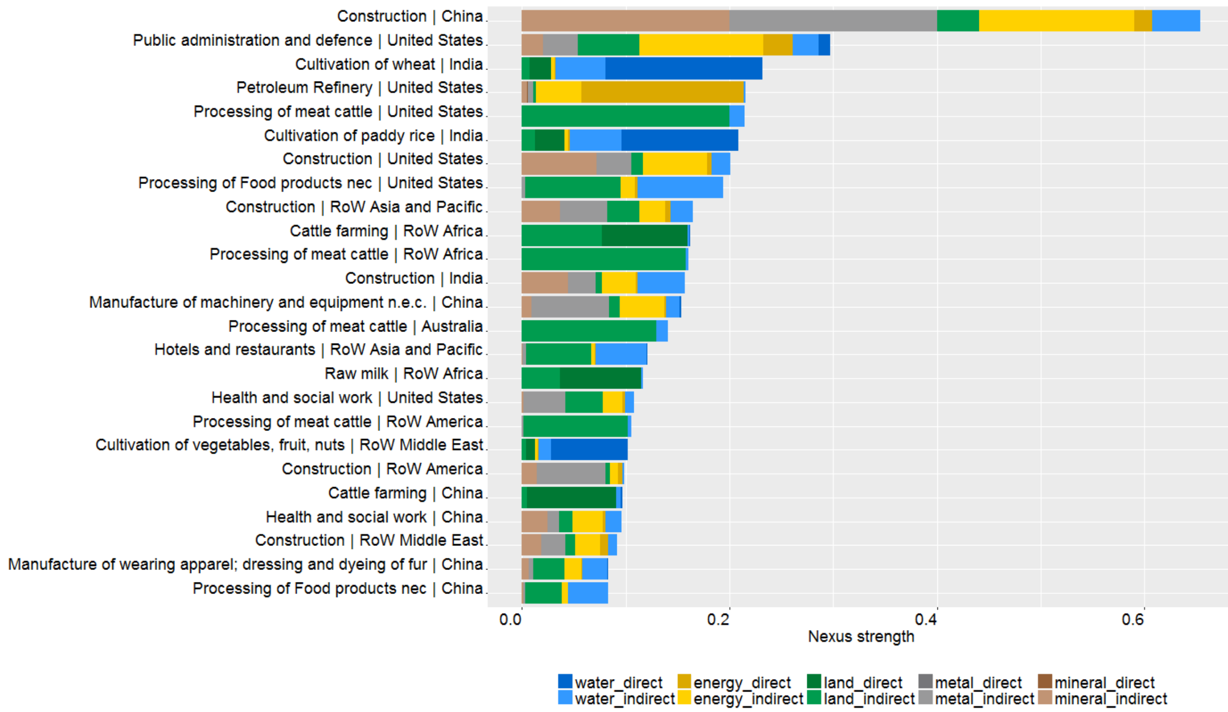

Figure 3. Nexus strength (with contribution by resource and type of use) of the top 25 product nexuses identified through consumption-based accounting. Dark shades represent direct use of resources, whereas light shades represent indirect use. RoW: rest-of-the-world; nec: not elsewhere classified.

For industry nexuses, the most relevant one is the water-land nexus taking place in agricultural activities. For crop cultivation activities, blue water consumption is the main driver of the nexus, especially in wheat and rice production and due to their high water requirements. On the other hand, land drives this nexus in animal farming activities, especially cattle farming, largely due to the use of extensive management systems (Robinson et al. 2014). Another important nexus is the water-energy nexus from coal power, which is driven by primary energy and where water is used mostly for cooling purposes. Energy also plays a role in the water-energy-land nexus of crop cultivation activities such as cereal grains, vegetables, and fruits, largely due to high mechanization and the use of fossil fuels in the operation of agricultural machinery.

For product nexuses, more complex nexuses are found, often including all five studied resources. Construction industries – led by China– are among the top nexuses found, with the presence of all resources and with important contributions of metals and minerals. Construction activities are associated with complex supply chains that require a diversity of resources. Taking the Chinese construction industry as an example, the immediate suppliers with the most associated or 'embedded' land use are 'hotels and restaurants' and 'manufacture of ceramic goods', both of which can eventually be traced back to direct land use due to cattle farming. Other relevant nexuses found are associated with public administration and defense (W+E+L+Me+Mi), crop cultivation (W+E+L) and processing of food products (W+E+L), again largely due to their complex supply chains.

<heading level 3> Alternative specifications of the nexus strength

When using sector instead of macroeconomic maxima (see Figures S4.1 and S4.2 in supporting information S4), industries and products can more easily reach a maximum nexus strength of one, as some industries and products from the largest economies (e.g. China and Russia) can dominate the global production and consumption. In this case, W+E+L+Me+Mi nexuses would be the strongest for both industry and product nexuses. On the other hand, the results based on the

TFC approach (see Figure S4.3 in supporting information S4) can be interpreted as a middle ground between the PBA and CBA approaches, as relevant industries and their related products identified in both approaches are somewhat combined. Service-based activities are still at the center stage, yet some key primary and secondary industries (e.g. farming activities) show a strong resource nexus. The TFC highlights those industries that induce the most output to produce their own output, and this is reflected in their associated resource nexus. Worthy of note is the increase in the role of water and energy, largely due to the outputs associated with energy production and suggesting the spread of the water-energy nexus from coal and nuclear electricity generation to manufacturing and agriculture industries. Lastly, the results when normalizing resource use according to economic output (to correct for economic size and potentially identify relevant nexuses at smaller scales) can be found in Figures S4.7 and S4.8. The normalized results show a larger role of land-intensive industries (e.g., cultivation of oil seeds) and mining industries in both large and medium-sized economies, which translate in a higher nexus strength of land, minerals and metals in the global resource nexus (see Figure S4.9). While this approach is valuable to identify relevant nexuses in smaller economies that would otherwise remain on a secondary level, it however introduces a systematic bias related to the price of products. For instance, strong nexuses are identified in industries and countries where economic outputs are relatively lower, such as construction materials in Africa.

The nexus strength indicator is influenced by the weighting of the various nodes, and it is thus important to further analyze its effect on the results. To this end, we have defined three weighting schemes based on various criteria (expert opinion or 'panel data (PD)', distance to planetary boundaries or ‘distance-to-target (DtT)’, and economic externalities or ‘shadow prices (SP)’) and re-calculated the nexus strength results accordingly (see supporting information S3 for the complete results). In general, the PD and DtT weightings illustrate the high importance of primary energy, while the SP weightings give land a notable importance. For industry nexuses, coal, gas and nuclear power gain positions in the top nexuses under the PD and DtT weightings via water-energy combinations, while agricultural activities monopolize the top nexuses via land-water combinations. For product nexuses, the PD and DtT weightings increase the importance of industries such as certain construction and manufacturing sectors, for which much energy is consumed in upstream activities; the SP weighting highlights the industries that rely on land-intensive supply chains, such as crop cultivation and food processing activities.

<heading level 2> Country-level nexus strength

The nexus strength by country and across the world are presented in Figure 4. The results correspond to the PBA approach (industry nexus) in order to reflect resource use taking place within national boundaries. The visualization approach is the same as that described in the section ‘Global overview of the nexus strength’ (see Figure 1). The country-level nexus strength values correspond to the aggregation of all the identified resource nexuses in a given country (see Figure 2 for the top industry-level nexuses). It is critical to note that the values of the vertices and edges have been scaled for visualization purposes only (relative values are maintained), and so these are shown proportionally bigger and wider, respectively. The same scaling factor is applied to all of the country-level values so that they are comparable among each other. Another scaling factor, also different from the one used in Figure 1, has been applied for the world values for visualization purposes only. Only those countries with the strongest nexus are displayed in Figure 4, and we refer to supporting information S5 for the complete results for country-specific considerations. Overall, the nexus strength is relatively consistent with the levels of domestic output, with the top economies generally displaying the largest nexus strength values (as illustrated by the shade intensity in Figure 4). Across countries, the nexus profiles display a considerable diversity, largely due to differences in the economic structure, domestic policy, technology and resource endowments.

Consistent with the global pattern illustrated in Figure 1, the water-land nexus appears to be the strongest nexus combination. Largely associated with farming activities, this nexus is particularly strong in India, U.S.A., and China, where a large fraction of the land and water resources are located. The availability and quality of resource endowments, however, introduce nuances in the strength and composition of farming-related nexuses. For instance, the types of crops (e.g., water-intensive such as rice or land-intensive such as grains), generally conditioned by local conditions but sometimes associated with domestic agriculture policies (see, for instance, the case of Northern China (Cai 2008)), also determine the relative importance of water and land in this nexus. The degree of mechanization and consequent use of fossil fuels in agriculture also induces energy-land and energy-water nexuses, for instance in the U.S.A. The second strongest nexus is the water-energy nexus from coal, gas and nuclear power industries, which is especially strong in the U.S.A. and China. These particular nexuses are well studied in the literature, and important drivers are the availability of coal/gas deposits and freshwater, domestic policy, and technology (Scott et al. 2011; Kahrl and Roland-Holst 2008). It also merits to highlight the significant and less-studied metal-mineral nexus caused from some metal and mineral mining activities, such as copper mining in Africa and stone quarrying in the U.S.A., which is sometimes associated with the presence of ‘accessory’ metals and minerals (Scott et al. 2005). Some mining activities are also associated with a considerable water-mineral nexus, as freshwater is used for mineral processing and dust suppression (Mudd 2008).

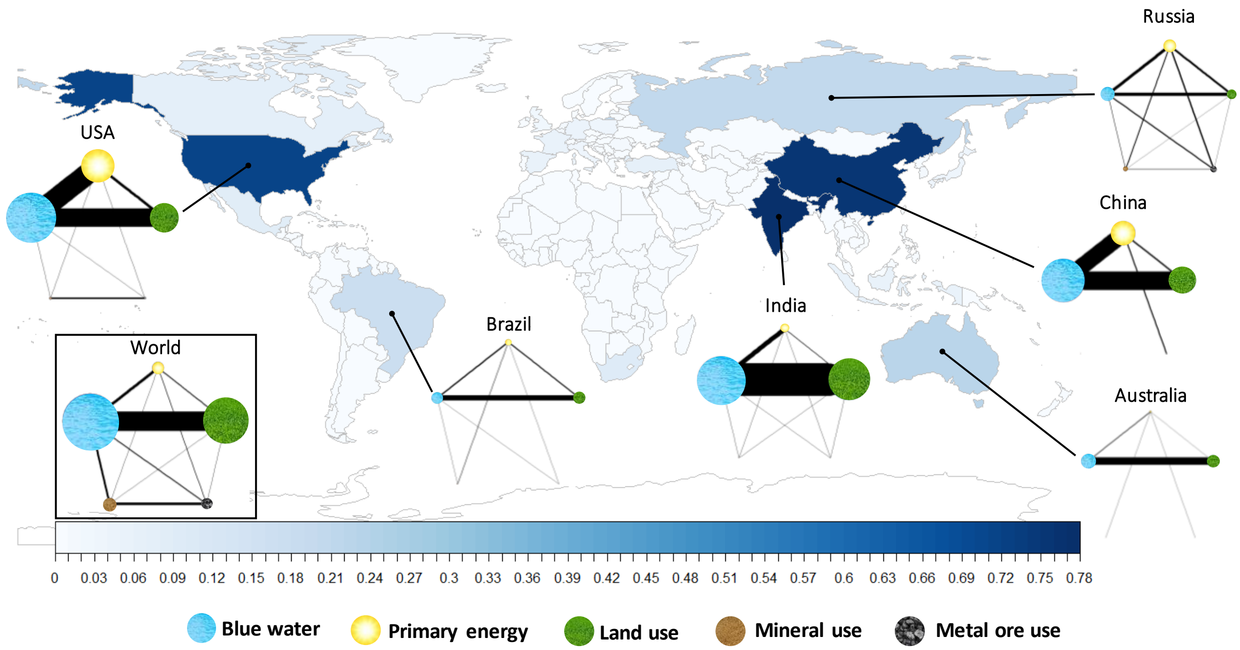

Figure 4. Nexus strength results by country and the world according to production-based accounting. Edges indicate the aggregated contribution of any given combination of two resources (for nexuses of more than two resources, all possible pairs are included), while vertices indicate the aggregated contribution of a given resource. A strong nexus between two resources, represented by a relatively wider edge, means that these resources are used simultaneously in large quantities across the global economy.

<heading level 1> Conclusions

Multi-regional input-output analysis (MRIOA) enables a most comprehensive and systematic investigation of resource use by production as well as consumption processes at various spatial scales (sub-national, national and worldwide). Such processes can induce, through a diversity of mechanisms, the simultaneous use of various resources, which can be conceived as a type of resource nexus. This manuscript addresses the question of how to identify and prioritize key resource nexus issues in light of alternative and sometimes conflicting interests. To address this question, we develop and apply a metric of 'nexus strength', which essentially uses linear goal programming (LGP) to select and weight combinations of simultaneous resource use (water, energy, land, metals and minerals) by country-industry and country-product according to variables of interest. The results give but a glimpse of the vast diversity and complexity of the global resource nexus (GRN), yet the observed general trends can be used to inform both future research and resource management practices.

First, adopting a consumption perspective allows to account for resource use taking place at various steps of the supply chain, leading to the identification of stronger and more complex resource nexuses. Some industries/products may be more relevant for the resource nexus than previously thought, such as construction and service-based activities. This perspective, seemingly underutilized in the study of nexus issues, presents large potential to mitigate such issues, for instance via consumer-oriented policies that target specific nexuses (e.g. promoting diet changes to mitigate the water-energy nexus (Marrin 2014)). It merits noting that this perspective (as opposed to its production counterpart) ignores the spatial dimension, and so resource use need not to take place in the same region. Indeed, resources become linked in the supply chain rather than in situ, and so this perspective offers complementary insights into combined resource use. To check whether multiple resources are being used in the same region, additional analyses should be conducted, such as structural path analysis (Peters and Hertwich 2006). Second, the consideration of multiple resources allows to identify nexus issues that may otherwise be overlooked using mainstream frameworks such as the water-energy-food nexus framework. For instance, the inclusion of metals and minerals suggests important metal-mineral, energy-metal, and water-mineral nexuses in both production and consumption perspectives. These insights open the doors to more comprehensive resource management practices leading to increased synergies and co-benefits. Regarding synergies, and in the context of sustainable consumption policies (e.g., EC (2008)), the five studied resources could be reduced simultaneously by fostering decreases in key final demand categories (e.g. meat products and construction activities). Regarding co-benefits, reductions in minerals (fertilizers) could be achieved in the context of land-water-food nexus policies in agriculture, for example by switching to crops that require less fertilizer (Weisler et al. 2001). Third, resource nexus issues differ greatly among countries, largely owing to output levels, economic structure, domestic policy, technology and resource endowments, and so nexus research could reveal different nodes of relevance for different countries and/or regions. Last but not least, the results also validate current research efforts at finer spatial scales, inasmuch as water, energy, and land present the strongest linkages globally both from a production and a consumption perspective.

This study is not without limitations, which can be described in terms of (1) LGP set-up, (2) indicators and (3) input-output (IO) methodology. First, our specific formulation is mostly focused on the absolute use of resources, and thus overlooks other aspects relevant to the nexus debate, such as resource availability and prices. However, the proposed LGP approach is flexible to incorporate such aspects in the form of goals, weights and constraints. Such considerations will depend on a variety of factors, such as the scale of analysis and local conditions, but more generally on the specific nexus-related research questions addressed. Second, resource use alone does not necessarily align fully with the importance of a given nexus issue. For instance, blue water may be abundant in regions where it is used in large quantities, or the presence of pollutants in water may influence its efficiency and uses. For these reasons, the use of indicators that reflect resource scarcity (e.g. scarcity-weighted footprints (Lenzen et al. 2013)), economic feasibility and/or quality can provide a better understanding of the importance of nexus issues. For instance, considerations of scarcity could yield relevant metal-energy nexuses in the context of emerging renewable energy technologies (Hertwich et al. 2015). Similarly, considerations of quality could highlight relevant water-energy and water-metal nexuses, for instance associated with shale gas (Kharak et al. 2013) and mining activities, respectively. Also, the use of more detailed resource indicators as nexus nodes (e.g., specific metals and croplands) could shed additional insights into concrete issues at various scales. The third and last limitation relates to known methodological limitations of IO approaches (Miller and Blair 2009). For example, insufficient disaggregation and the use of monetary values can misestimate the importance of certain economic flows, such as water flows being undervalued due to inadequate pricing (Rogers et al. 2002). These limitations could be addressed, for instance, by using disaggregation of IOTs (Lenzen 2011) (e.g. through hybrid models) and physical input-output tables (Hubacek and Giljum

2003). Also, our approach does not capture trends as it uses a single year IO database, an issue that could be addressed by using existing time series.

In conclusion, recent advancements in IOA, and especially in the field of MRIOA, offer exceptional potential to understand and leverage the complexity and diversity of GRN issues. While inherent limitations will remain, this renewed perspective can be used to screen the most significant nexus challenges globally, in turn guiding analyses at finer sectorial and spatial scales, as well as regional planning and policy making.

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References

Allan, J. A. 1998. Virtual water: a strategic resource. *Ground water* 36(4): 545.

Andrews-Speed, P., R. Bleischwitz, T. Boersma, C. Johnson, G. Kemp, and S. D. VanDeveer. 2012. *The global resource nexus : the struggles for land, energy, food, water, and minerals*. Washington, DC: Transatlantic Acad.

Andrews-Speed, P., R. Bleischwitz, T. Boersma, C. Johnson, G. Kemp, and S. D. VanDeveer. 2014. *Want, waste or war?: the global resource nexus and the struggle for land, energy, food, water and minerals*: Routledge.

Anu, R., B. Dana, N. Ajay Singh, F. Andrew, B. Shelly, B. Bhavik, C. Elliot, and R.-G. Ashish. 2017. An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India. *Environmental Research Letters* 12(2): 025008.

Bartos, M. D. and M. V. Chester. 2014. The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona. *Environmental Science & Technology* 48(4): 2139-2149.

Bazilian, M., H. Rogner, M. Howells, S. Hermann, D. Arent, D. Gielen, P. Steduto, A. Mueller, P. Komor, R. S. J. Tol, and K. K. Yumkella. 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* 39(12): 7896-7906.

Bekkers, F., M. Gehem, M. de Ridder, S. de Jong, and W. Auping. 2014. *The Global Resource Nexus: IMPACT ON SUSTAINABLE SECURITY OF SUPPLY OF AGRI-FOOD IMPORTS FOR THE NETHERLANDS*: The Hague Centre for Strategic Studies.

Bizikova, L., D. Roy, D. Swanson, H. D. Venema, and M. McCandless. 2013. *The water-energy-food security nexus: Towards a practical planning and decision-support framework for landscape investment and risk management*: International Institute for Sustainable Development.

Cai, X. 2008. Water stress, water transfer and social equity in Northern China—Implications for policy reforms. *Journal of Environmental Management* 87(1): 14-25.

Clift, R. and A. Druckman. 2015. *Taking Stock of Industrial Ecology*: Springer.

Conway, D., E. A. Van Garderen, D. Deryng, S. Dorling, T. Krueger, W. Landman, B. Lankford, K. Lebek, T. Osborn, and C. Ringler. 2015. Climate and southern Africa's water-energy-food nexus. *Nature Climate Change* 5(9): 837-846.

Dietzenbacher, E., M. Lenzen, B. Los, D. Guan, M. L. Lahr, F. Sancho, S. Suh, and C. Yang. 2013. INPUT–OUTPUT ANALYSIS: THE NEXT 25 YEARS. *Economic Systems Research* 25(4): 369-389.

Duan, C. and B. Chen. 2017. Energy–water nexus of international energy trade of China. *Applied Energy* 194: 725-734.

Duchin, F. and A. E. Steenge. 1999. Input-output analysis, technology and the environment. *Handbook of Environmental and Resource Economics, Edward Elgar, Cheltenham, UK*: 1037-1059.

EC. 2008. *Communiction on the sustainable consumption and production and sustainable industrial policy action plan. COM(2008)397*.

Eder, P. and M. Narodoslawsky. 1999. What environmental pressures are a region's industries responsible for? A method of analysis with descriptive indices and input–output models1. *Ecological Economics* 29(3): 359-374.

Fath, B. D. and B. C. Patten. 1999. Review of the Foundations of Network Environ Analysis. *Ecosystems* 2(2): 167-179.

Feltrin, A. and A. Freundlich. 2008. Material considerations for terawatt level deployment of photovoltaics. *Renewable energy* 33(2): 180-185.

Feng, K., K. Hubacek, Y. L. Siu, and X. Li. 2014. The energy and water nexus in Chinese electricity production: A hybrid life cycle analysis. *Renewable and Sustainable Energy Reviews* 39: 342-355.

Funtowicz, S. O., J. M. Alier, G. Munda, and J. R. Ravetz. 1999. *Information tools for environmental policy under conditions of complexity*: Office for official publications of the European communities.

Gallego, B. and M. Lenzen. 2005. A consistent input–output formulation of shared producer and consumer responsibility. *Economic Systems Research* 17(4): 365-391.

Giurco, D., B. McLellan, D. M. Franks, K. Nansai, and T. Prior. 2014. Responsible mineral and energy futures: views at the nexus. *Journal of Cleaner Production* 84: 322-338.

Graedel, T., A. Elshkaki, and E. Van der Voet. 2014. Entangled Circles: Energy and Its Resource Connections. In *The colours of energy: Essays on the future of our energy system*, edited by K. G.J. and V. B. Amsterdam, the Netherlands: Shell International B.V.

Graedel, T. E. and E. van der Voet. 2010. *Linkages of sustainability*: Mit Press Cambridge, MA:.

Gu, A., F. Teng, and Y. Wang. 2014. China energy-water nexus: Assessing the water-saving synergy effects of energy-saving policies during the eleventh Five-year Plan. *Energy Conversion and Management* 85: 630-637.

Guo, S. and G. Q. Shen. 2015. Multiregional Input–Output Model for China's Farm Land and Water Use. *Environmental Science & Technology* 49(1): 403-414.

Hertwich, E. G. and G. P. Peters. 2009. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environmental Science & Technology* 43(16): 6414-6420.

Hertwich, E. G., T. Gibon, E. A. Bouman, A. Arvesen, S. Suh, G. A. Heath, J. D. Bergesen, A. Ramirez, M. I. Vega, and L. Shi. 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences* 112(20): 6277-6282.

Howells, M., S. Hermann, M. Welsch, M. Bazilian, R. Segerstrom, T. Alfstad, D. Gielen, H. Rogner, G. Fischer, H. van Velthuizen, D. Wiberg, C. Young, R. A. Roehrl, A. Mueller, P. Steduto, and I. Ramma. 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nature Clim. Change* 3(7): 621-626.

Hubacek, K. and S. Giljum. 2003. Applying physical input–output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics* 44(1): 137-151.

Ignizio, J. P. 1985. *Introduction to linear goal programming*: Sage publishing.

IPCC. 1996. *Revised 1996 IPCC guidelines for national greenhouse gas inventories. v. 1: Greenhouse gas inventory reporting instructions.-v. 2: Greenhouse gas inventory workbook.-v. 3: Greenhouse gas inventory reference manual*.

Jeong, K.-J. 1984. The relation between two different notions of direct and indirect input requirements. *Journal of Macroeconomics* 6(4): 473-476.

Kahrl, F. and D. Roland-Holst. 2008. China's water–energy nexus. *Water Policy* 10(S1): 51-65.

Kenway, S. J., P. A. Lant, A. Priestley, and P. Daniels. 2011. The connection between water and energy in cities: a review. *Water Science and Technology* 63(9): 1983.

Kharak, Y. K., J. J. Thordsen, C. H. Conaway, and R. B. Thomas. 2013. The Energy-Water Nexus: Potential Groundwater-Quality Degradation Associated with Production of Shale Gas. *Procedia Earth and Planetary Science* 7: 417-422.

Leavesley, G. H., S. L. Markstrom, M. S. Brewer, and R. J. Viger. 1996. The Modular Modeling System (MMS) -- The Physical Process Modeling Component of a Database-Centered Decision Support System for Water and Power Management. In *Clean Water: Factors that Influence Its Availability, Quality and Its Use: International Clean Water Conference held in La Jolla, California, 28–30 November 1995*. Dordrecht: Springer Netherlands.

Lenzen, M. 2011. AGGREGATION VERSUS DISAGGREGATION IN INPUT–OUTPUT ANALYSIS OF THE ENVIRONMENT. *Economic Systems Research* 23(1): 73-89.

Lenzen, M., D. Moran, A. Bhaduri, K. Kanemoto, M. Bekchanov, A. Geschke, and B. Foran. 2013. International trade of scarce water. *Ecological Economics* 94: 78-85.

Lenzen, M., A. Geschke, T. Wiedmann, J. Lane, N. Anderson, T. Baynes, J. Boland, P. Daniels, C. Dey, J. Fry, M. Hadjikakou, S. Kenway, A. Malik, D. Moran, J. Murray, S. Nettleton, L. Poruschi, C. Reynolds, H. Rowley, J. Ugon, D. Webb, and J. West. 2014. Compiling and using input–output frameworks through collaborative virtual laboratories. *Science of The Total Environment* 485–486: 241-251.

Leontief, W. 1970. Environmental repercussions and the economic structure: an input-output approach. *The review of economics and statistics* 52(3): 262-271.

Li, X., K. Feng, Y. L. Siu, and K. Hubacek. 2012. Energy-water nexus of wind power in China: The balancing act between CO2 emissions and water consumption. *Energy Policy* 45: 440-448.

Liu, J., H. Mooney, V. Hull, S. J. Davis, J. Gaskell, T. Hertel, J. Lubchenco, K. C. Seto, P. Gleick, C. Kremen, and S. Li. 2015. Systems integration for global sustainability. *Science* 347(6225).

Lofman, D., M. Petersen, and A. Bower. 2002. Water, Energy and Environment Nexus: The California Experience. *International Journal of Water Resources Development* 18(1): 73-85.

Löschel, A., J. Johnston, M. Delucchi, T. Demayo, D. Gautier, D. L. Greene, J. M. Ogden, S. Rayner, and E. Worrell. 2009. Stocks, Flows, and Prospects of Energy. In *Linkages of Sustainability*, edited by T. Graedel and E. Van der Voet: The MIT press.

Marrin, D. 2014. Reducing water and energy footprints via dietary changes among consumers. *Int J Nutr Food Sci* 3: 361-369.

Marsh, D. M. 2008. The water-energy nexus: a comprehensive analysis in the context of New South Walesthesis, Faculty of Engineering and Information Technology Sydney University of Technology.

Meyfroidt, P., T. K. Rudel, and E. F. Lambin. 2010. Forest transitions, trade, and the global displacement of land use. *Proceedings of the National Academy of Sciences* 107(49): 20917-20922.

Milana, C. 1985. DIRECT AND INDIRECT REQUIREMENTS FOR GROSS OUTPUT IN INPUT–OUTPUT ANALYSIS(*). *Metroeconomica* 37(3): 283-291.

Miller, R. E. and P. D. Blair. 2009. *Input-output analysis: foundations and extensions*. Cambridge, United Kingdom: Cambridge University Press.

Mo, W., R. Wang, and J. B. Zimmerman. 2014. Energy–Water Nexus Analysis of Enhanced Water Supply Scenarios: A Regional Comparison of Tampa Bay, Florida, and San Diego, California. *Environmental Science & Technology* 48(10): 5883-5891.

Mudd, G. M. 2008. Sustainability Reporting and Water Resources: a Preliminary Assessment of Embodied Water and Sustainable Mining. *Mine Water and the Environment* 27(3): 136.

Oers, L. v. and A. Tukker. 2016. *Development of a Resource Efficiency Index of Nations*

Okadera, T., Y. Geng, T. Fujita, H. Dong, Z. Liu, N. Yoshida, and T. Kanazawa. 2015. Evaluating the water footprint of the energy supply of Liaoning Province, China: A regional input–output analysis approach. *Energy Policy* 78: 148-157.

Oosterhaven, J. 1981. *Interregional input-output analysis and dutch regional policy problems*.

Peters, G. P. and E. G. Hertwich. 2006. Structural analysis of international trade: Environmental impacts of Norway. *Economic Systems Research* 18(2): 155-181.

Plevin, R. J., Jones, A. D., Torn, M. S., & Gibbs, H. K. (2010). Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. Environmental Science and Technology 44 (21): 8015–8021.

Rijsberman, F. R. 2006. Water scarcity: Fact or fiction? *Agricultural Water Management* 80(1–3): 5-22.

Robinson, T. P., G. R. W. Wint, G. Conchedda, T. P. Van Boeckel, V. Ercoli, E. Palamara, G. Cinardi, L. D'Aietti, S. I. Hay, and M. Gilbert. 2014. Mapping the Global Distribution of Livestock. *PLoS One* 9(5): e96084.

Rogers, P., R. d. Silva, and R. Bhatia. 2002. Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. *Water Policy* 4(1): 1-17.

Romero-Lankao, P., T. McPhearson, and D. J. Davidson. 2017. The food-energy-water nexus and urban complexity. *Nature Clim. Change* 7(4): 233-235.

Scott, C. A., S. A. Pierce, M. J. Pasqualetti, A. L. Jones, B. E. Montz, and J. H. Hoover. 2011. Policy and institutional dimensions of the water–energy nexus. *Energy Policy* 39(10): 6622-6630.

Scott, P. W., J. M. Eyre, D. J. Harrison, and A. J. Bloodworth. 2005. Markets for industrial mineral products from mining waste. *Geological Society, London, Special Publications* 250(1): 47-59.

Sovacool, B. K. and K. E. Sovacool. 2009. Identifying future electricity–water tradeoffs in the United States. *Energy Policy* 37(7): 2763-2773.

Srilatha, B. 1982. Rural Energy Scarcity and Nutrition: A New Perspective. *Economic and Political Weekly* 17(9): 329-333.

Suh, S. 2009. *Handbook of Input-Output Economics in Industrial Ecology*, *Eco-Efficiency in Industry and Science*: Springer.

Szyrmer, J. M. 1992. Input—Output Coefficients and Multipliers from a Total-Flow Perspective. *Environment and Planning A* 24(7): 921-937.

Tukker, A. and E. Dietzenbacher. 2013. GLOBAL MULTIREGIONAL INPUT–OUTPUT FRAMEWORKS: AN INTRODUCTION AND OUTLOOK. *Economic Systems Research* 25(1): 1-19.

Tukker, A., T. Bulavskaya, S. Giljum, A. de Koning, S. Lutter, M. Simas, K. Stadler, and R. Wood. 2014. The Global Resource Footprint of Nations—Carbon, Water, Land and Materials Embodied in Trade and Final Consumption Calculated with Exiobase 2.1: The Netherlands Organisation for Applied Scientific Research.

Voinov, A. and H. Cardwell. 2009. The Energy-Water Nexus: Why Should We Care? *Journal of Contemporary Water Research & Education* 143(1): 17-29.

Wang, R. and J. Zimmerman. 2016. Hybrid Analysis of Blue Water Consumption and Water Scarcity Implications at the Global, National, and Basin Levels in an Increasingly Globalized World. *Environmental Science & Technology* 50(10): 5143-5153.

Wang, S. and B. Chen. 2016. Energy–water nexus of urban agglomeration based on multiregional input–output tables and ecological network analysis: A case study of the Beijing–Tianjin–Hebei region. *Applied Energy* 178: 773-783.

Weinzettel, J., E. G. Hertwich, G. P. Peters, K. Steen-Olsen, and A. Galli. 2013. Affluence drives the global displacement of land use. *Global Environmental Change* 23(2): 433-438.

Weisler, F., T. Behrens, and W. J. Horst. 2001. The role of nitrogen-efficient cultivars in sustainable agriculture. *The Scientific World Journal* 1: 61-69.

White, D. J., K. Hubacek, K. Feng, L. Sun, and B. Meng. 2017. The Water-Energy-Food Nexus in East Asia: A tele-connected value chain analysis using inter-regional input-output analysis. *Applied Energy*.

Wiedmann, T., H. C. Wilting, M. Lenzen, S. Lutter, and V. Palm. 2011. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecological Economics* 70(11): 1937-1945.

Wiedmann, T. O., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, and K. Kanemoto. 2015. The material footprint of nations. *Proceedings of the National Academy of Sciences* 112(20): 6271-6276.

Wood, R., K. Stadler, T. Bulavskaya, S. Lutter, S. Giljum, A. de Koning, J. Kuenen, H. Schütz, J. Acosta-Fernández, A. Usubiaga, M. Simas, O. Ivanova, J. Weinzettel, J. Schmidt, S. Merciai, and A. Tukker. 2014. Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability* 7(1): 138-163.

Wu, X. D. and G. Q. Chen. 2017. Energy and water nexus in power generation: The surprisingly high amount of industrial water use induced by solar power infrastructure in China. *Applied Energy* 195: 125-136.

Yan, X. and J. Ge. 2017. The Economy-Carbon Nexus in China: A Multi-Regional Input-Output Analysis of the Influence of Sectoral and Regional Development. *Energies* 10(1): 93.

Zhang, X. and V. V. Vesselinov. 2016. Energy-water nexus: Balancing the tradeoffs between two-level decision makers. *Applied Energy* 183: 77-87.

Zimmerman, R., Q. Zhu, and C. Dimitri. 2016. Promoting resilience for food, energy, and water interdependencies. *Journal of Environmental Studies and Sciences* 6(1): 50-61.

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