



## 13 Summary

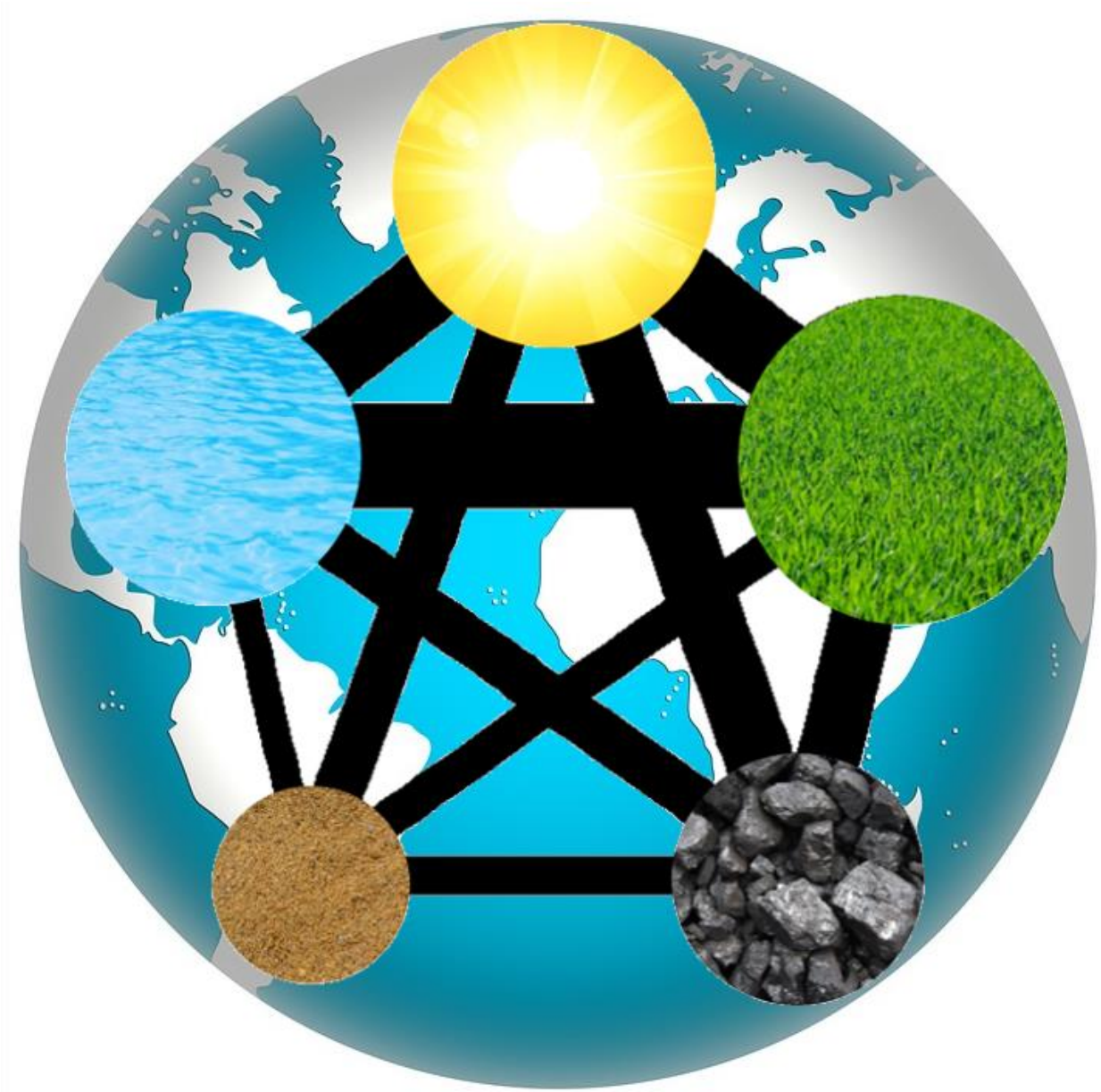
14

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

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

35 Graphical abstract

36



37

## 38 <heading level 1> Introduction

39

40 The limited access to crucial resources is increasingly perceived as a major constraint for  
41 environmental and economic sustainability (Graedel and van der Voet 2010; Liu et al. 2015). A  
42 number of technological systems, such as energy and food production, face challenges related to  
43 resource supply risk (Graedel et al. 2014; Graedel and van der Voet 2010). Some examples are  
44 the water constraints on electricity (Sovacool and Sovacool 2009) and food (Rijsberman 2006)  
45 production, as well as the scarcity of certain metals used for hydrogen fuel cells (Löschel et al.  
46 2009) and photovoltaic technologies (Feltrin and Freundlich 2008). Such constraints are often  
47 related to political conflict, economic feasibility, institutional barriers as well as the physical  
48 availability of supporting natural resources (Andrews-Speed et al. 2012). In response to these  
49 challenges, the ‘nexus framework’ was proposed to aid resource management practices at meso-  
50 and macro scales (Liu et al. 2015).

51 The nexus framework focuses on the linkages between socio-ecological systems, and can help  
52 anticipate unforeseen consequences, identify trade-offs and co-benefits, and find optimal  
53 solutions between competing interests (Bizikova et al. 2013; Howells et al. 2013). When applied  
54 to natural resources alone, some authors speak of the ‘resource nexus’, and define it as the  
55 “linkages between different natural resources and raw materials that arise from economic,  
56 political, social, and natural processes” (Andrews-Speed et al. 2014). The (resource) nexus realm  
57 encompasses multiple focuses, such as competing use patterns, substitutability, and socio-  
58 political repercussions (Andrews-Speed et al. 2014). The nexus focus conceived here relates to  
59 the combined use of natural resources arising from economic processes, that is, the simultaneous

60 use of two or more natural resources in productive activities or as a result of consumption.  
61 Following this approach, the goal of this article is twofold: (1) to identify key hotspots of  
62 combined resource use within the current global economic systems, and (2) to gain insight into  
63 the reasons behind the linkages between resources, namely co-occurrence, choice of technology,  
64 supply chain structure, etc.

65

## 66 <heading level 2> Current approaches to the resource nexus

67

68 Nexus studies generally deal with the (inter)dependencies between pre-defined nexus nodes  
69 (e.g. natural resources) and their related socio-economic agents (e.g. industries), usually through  
70 case studies. For example, when studying the water-energy nexus, the scope is typically to  
71 address the water used for energy production and/or the energy used for water supply in a  
72 particular case. Resource nexuses were initially approached during the 1980s in the form of food-  
73 energy nexus issues (Srilatha 1982), and such two-node patterns still dominate the literature.  
74 According to Liu et al. (2015), 80% of all nexus studies analyzed only two nodes, of which energy-  
75 water, food-water, and energy-food have been the most popular configurations. Additional  
76 nodes traditionally included in nexus studies are land use and greenhouse gas (GHG) emissions  
77 (Liu et al. 2015) . Most recently, there has been a great public and scholarly focus on the food-  
78 energy-water (FEW) nexus (Bazilian et al. 2011; Conway et al. 2015). The focus on a limited  
79 number of nodes can be justified by the *a priori* relevance of the selected nodes, the lack of data,  
80 as well as the aim to limit the complexity of the analyses. The consideration of additional

81 supporting resources is however critical in some cases, as illustrated in the controversy  
82 surrounding biofuels. More specifically, the consideration of biofuels' GHG emissions from land  
83 use change, which was beyond the initial scope of the water-energy nexus, proved to be a key  
84 determinant of the overall carbon performance of biofuels (Plevin et al. 2010). Furthermore,  
85 material resources, such as metals and minerals, have not been the focus of nexus studies until  
86 recently (Graedel and van der Voet 2010; Graedel et al. 2014; Bekkers et al. 2014; Giurco et al.  
87 2014), and there remains a lack of quantitative analyses to assess whether these are important  
88 nodes. The consideration of material resources as part of the nexus framework could unveil  
89 valuable insights, such as potential co-benefits from energy and water conservation and/or  
90 efficiency practices (Andrews-Speed et al. 2012). This resonates with complementary concepts  
91 such as circular economy, resource efficiency and industrial ecology (Clift and Druckman 2015).

92 Nexus issues have been studied at various geographical and economic levels, such as urban (Anu  
93 et al. 2017; Romero-Lankao et al. 2017; Kenway et al. 2011), regional (Lofman et al. 2002; Bartos  
94 and Chester 2014), and national levels (Kahrl and Roland-Holst 2008), yet the global scale remains  
95 largely unexplored. While some nexus issues are mostly location-dependent (e.g. water use from  
96 constrained reservoirs) (Bekkers et al. 2014), there is an explicitly global dimension to most nexus  
97 issues as local constraints can be mediated by trade, as illustrated by virtual water trade (Allan  
98 1998; Wang and Zimmerman 2016) and land use displacement (Meyfroidt et al. 2010; Weinzettel  
99 et al. 2013). Moreover, most of the nexus literature focuses on particular industries, such as food  
100 and energy, where large quantities of natural resources are directly used. In consequence, those  
101 industries with no immediate resource implications or in which resource interdependencies  
102 reside across the ever more complicated and global supply chains are overlooked. For instance,

103 service-based industries such as construction, can indirectly induce considerable resource use  
104 (electricity production, metal products, etc.). Comprehensive analyses across the whole economy  
105 thus have the ability to identify previously unnoticed nexus issues. Against this background, three  
106 research avenues present unexplored potential: (1) the simultaneous study of multiple natural  
107 resources — including material resources— as nexus nodes, (2) the study of nexus issues at the  
108 global scale, and (3) the inclusion of all economic agents as mediators of nexus issues.

109

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

111

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

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

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

138 Pioneering works on the interplay between the nexus framework and IOA addressed the water-  
139 energy nexus through case studies. Among these, Marsh (2008) suggested various IO techniques  
140 to address multiple dimensions of nexus issues (linkage analysis, dependency analysis, multiplier  
141 analysis and scenario analysis), while Kahrl and Roland-Holst (2008) identified three relevant  
142 metrics to quantify the nexus: physical, monetary and distributive. These early studies  
143 highlighted the limited representation of capital stocks as well as the resolution and static nature  
144 of IO tables as shortcomings, and these were later dealt with to some extent by integrating  
145 process-based life cycle data in the form of hybrid IO models (Mo et al. 2014; Gu et al. 2014; Li



146 et al. 2012; Wu and Chen 2017). Other authors highlighted the inattention to local conditions  
147 (e.g. resource scarcity and quality) caused by the limited spatial resolution of IO tables, and  
148 proposed the use of stress-based indexes (Feng et al. 2014) and subnational IO tables (Okadera  
149 et al. 2015). More recently, and in the context of the increasing importance of interregional and  
150 international trade, nexus studies applied MRIO (Miller and Blair 2009; Duchin and Steenge 1999)  
151 and ecological network analysis (ENA) (Fath and Patten 1999) to explore structural properties  
152 and sectorial interactions of extended economic systems (Guo and Shen 2015; Wang and Chen  
153 2016; Duan and Chen 2017; White et al. 2017; Yan and Ge 2017).

154

## 155 <heading level 2> Resource nexus metrics

156

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

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

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

183

184 <heading level 1> Methods and data sources

185

186 This section first presents the scope of the study in terms of temporal and spatial boundaries,  
187 accounting approaches and indicators used, as well as the sources of data. Following is

188 presented a method for multi-regional input-output analysis (MRIOA) for both production and  
189 consumption perspectives. The formulation of a performance indicator to identify and rank  
190 nexuses, labelled as 'nexus strength', concludes this section.

191

## 192 <heading level 2> Scope and sources of data

193

194 The scope of this study is the global economy, represented by the MRIO database EXIOBASE v3.3  
195 (Wood et al. 2014). For the years 1995-2014, EXIOBASE v3.3 contains all monetary transactions  
196 between 163 industries and final users across 49 regions (44 of the largest world economies and  
197 5 continent regions aggregating the rest of the world). Thus, 7,987 (i.e. 49×163) country-specific  
198 industries specifies the global economy each year. EXIOBASE v3.3 also contains multiple  
199 environmental accounts (direct resource use and emissions) in physical units at the same industry  
200 and country detail and time resolution. Focusing on the impacts of natural resource extraction,  
201 this study considers five critical nodes of the GRN: use of primary energy carriers (referred to as  
202 just 'energy'), consumption of blue water (fresh surface and groundwater) ('water'), use of  
203 (arable) land ('land'), domestic extraction used of metal ores ('metals') and domestic extraction  
204 used of non-metallic minerals ('minerals'). These resources, especially the first three, have been  
205 a popular focus of the nexus literature (Andrews-Speed et al. 2014; Liu et al. 2015; Graedel and  
206 van der Voet 2010), yet rarely assessed simultaneously. It merits noting that the chosen nexus  
207 nodes have a heterogeneous composition (e.g., 'metals' include multiple types of ores), yet have  
208 been aggregated to make the analysis more concise and interpretable. For the same reasons, and

209 when possible, we have selected broad categories as a proxy of more detailed resources, such as  
210 land use as a proxy of various types of biomass (crops, timber, fish products, etc.) and primary  
211 energy as a proxy of various energy carriers (fossil fuels, uranium, waste, etc.). We have also  
212 excluded food, a common nexus node, as it is generally an economic product rather than a  
213 natural resource. We have chosen the year 2007 as it is the reference year for which the highest  
214 quality data is available. A detailed description of the regions, industries and resources included  
215 in this study is presented in supporting information S1.

216 For the main analysis, we analyze the GRN from the two main accounting perspectives in IOA,  
217 namely the production-based accounting (PBA) and the consumption-based accounting (CBA  
218 ). When following the PBA, we speak of an industry nexus, whereas, when following the CBA, we  
219 speak of a product nexus. The PBA is based on the territorial-based approach (IPCC 1996) and  
220 includes all resource use taking place within given political boundaries. Resource use of an  
221 industry thus corresponds to its direct resource extractions, commonly from within a  
222 local/regional territory, used as factors of production. The CBA emerged with the aim to account  
223 for the driving forces for resource use associated with consumption (Eder and Narodoslowsky  
224 1999; Tukker et al. 2014; Hertwich and Peters 2009; Wiedmann et al. 2015). In this case, the  
225 resource use corresponds to all resources used along the supply chains, i.e. both direct and  
226 indirect resource use, that contributes to the provision of a finished product or service for final  
227 consumption. The MRIO database further enables tracing resource use throughout global supply  
228 chain to the final consumption in individual nations. As such, PBA and CBA offer complementary  
229 insights into the GRN. The PBA captures actors that directly extract and use multiple natural  
230 resources, and so nexuses relate mostly to technology requirements (e.g. land, minerals, and

231 water to produce food). On the other hand, the CBA traces direct resource use along supply  
232 chains to final consumers of goods and services, illuminating the ultimate drivers of the nexus  
233 and the resource (inter)dependencies (e.g. energy to deliver drinking water) essential to realize  
234 the ultimate human needs. To account for the overall effect of an industry rather than its direct  
235 contribution or the effect attributable to final demand, alternative approaches, such as the total  
236 flow concept (TFC) (Szyrmer 1992; Jeong 1984), have been proposed. The TFC can be understood  
237 as a production-based footprint, as it estimates the direct plus indirect inputs associated with  
238 each industry's output. Although its use for impact analysis suffers from non-additivity (Milana  
239 1985; Gallego and Lenzen 2005) (indirect inputs are systematically double-counted), we replicate  
240 our proposed approach with the TFC for the purpose of discussing its potential value for the study  
241 of the resource nexus. We provide a detailed description of the TFC calculations in supporting  
242 information S2.

243

## 244 <heading level 2> Input-output analysis

245

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

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

253

$$254 \quad e_{r,i}^{PP} = \sum_{k=1}^h F_{k,i} \quad (Eq. 1)$$

255

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

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

270

271 
$$e_{r,i}^{CP} = s_r x; \quad (Eq. 2)$$

272 
$$x = (I - A)^{-1}y = Ly; \quad (Eq. 3)$$

273

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

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

283

284 
$$ei_{r,i}^{CP} = s_r x^*$$

285 
$$\text{with } x^* = x - y \quad (Eq. 4)$$

286

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

289

290 
$$ed_{r,i}^{CP} = e_{r,i}^{CP} - ei_{r,i}^{CP} \quad (Eq. 5)$$

291

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

296

297 <heading level 2> Nexus strength

298

299 Using the equations presented in the previous section, resource use associated with any given  
300 industry or product is calculated for all five selected resources. In the context of the study of  
301 resource nexus issues, this presents two challenges. First, how do we define a resource nexus?  
302 And second, how can we identify the most relevant or 'stronger' nexuses if each resource has  
303 different units? Mathematically, the first issue involves a normative decision on the minimum  
304 number of resources that constitute a nexus, as well as regarding a given threshold that  
305 determines the minimum use that will be tolerated for a nexus to take place. For example, if a  
306 given industry uses a significant quantity of water and a marginal amount of energy, one can call  
307 into question whether it constitutes a water-energy nexus. The second issue is commonly  
308 associated with the concept of environmental multi-dimensionality or incommensurability  
309 (Funtowicz et al. 1999). As an example, let us assume that industry A uses 10 units of water and  
310 5 units of energy, whereas industry B uses 5 units of water and 10 units of energy. When



311 evaluating which industry presents the most challenging nexus, the result will depend on how  
312 the importance of each resource is weighted (based on relative use, scarcity, price, etc.). In this  
313 analysis, we address both issues through linear goal programming (LGP), a type of multi-objective  
314 optimization model within the umbrella of multi-criteria decision analysis (Ignizio 1985). LGP can  
315 be used straightforwardly to study multiple environmental issues within the Leontief model  
316 (Miller and Blair 2009).

317 An LGP set-up follows the basic structure of linear programming, that is, an objective function  
318 (Eq. 7) that is optimized following a set of constraints (Eqs. 8-14). LGP deals with the issue of  
319 multi-dimensionality by calculating unitless deviations from pre-defined goals. These deviations  
320 are then optimized, i.e., minimized or maximized, in the objective function. In our case, we set  
321 the goals, for each resource analyzed, as the macroeconomic (for all industries) or the sector (for  
322 all industries of the same type) maximum resource use, respectively (Eq. 9-13). The goal thus acts  
323 as an undesired reference. The deviation represents the ratio of the use of a resource by a given  
324 industry to the use of the same resource by the industry having the highest resource use at the  
325 macroeconomic/sector level. In order to find the most resource-intensive industry, we define a  
326 maximization objective function (Eq. 7). It is common to weight the deviations of different  
327 resources, possibly with some constraint setup (Eq. 8), to reflect their relative importance. The  
328 imposition of other constraints allows for dealing with the issue of the nexus definition, as a set  
329 of constraints can ensure both a minimum number of different resources and a minimum  
330 quantity of each resource use. In our case (Eq. 14), we set a minimum of two resources and a  
331 minimum relative deviation (as a proxy of resource use) of 1% (i.e.  $h=1\%$ ). That is, for any given  
332 combination of at least two resources, the highest deviation among all resources used is taken as

333 a reference, and any other deviation must be no less than 1% or otherwise it is excluded from  
334 the combination. This threshold ensures that a given nexus is not composed of any resource with  
335 a trivial use. We label the result of the objective function as the ‘nexus strength’ of a particular  
336 industry or product. In turn, each single deviation can be understood as the contribution of each  
337 resource to the nexus strength. The nexus strength metric ranges from 1 (maximum use for all  
338 resources) to 0 (no use of resources). By iterating the proposed LGP approach a given number of  
339 times, we can calculate which industries have the highest nexus strength. Differently from a  
340 simple ranking procedure, linear programming approaches are much more efficient in finding  
341 optimal solutions, as all possible combinations need not to be evaluated thanks to the use of  
342 constraints. Mathematically, the LGP approach to find the strongest nexus can be formulated as  
343 follows:

344

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

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

347 *Subject to:*

348 
$$\sum_R^n (p_n) = 1 ; R = \{w, e, l, me, mi\}$$
 (Eq. 8)

349 
$$d_{w,i} = \frac{e_{w,i}^{PP|CP}}{g_w} ; g_w = \max(\{e_{w,i}^{PP|CP}\})_{i \in I|J}$$
 (Eq. 9)

350 
$$d_{e,i} = \frac{e_{e,i}^{PP|CP}}{g_e} ; g_e = \max(\{e_{e,i}^{PP|CP}\})_{i \in I|J}$$
 (Eq. 10)

351 
$$d_{l,i} = \frac{e_{l,i}^{PP|CP}}{g_l} ; g_l = \max(\{e_{l,i}^{PP|CP}\})_{i \in I|J} \text{ (Eq. 11)}$$

352 
$$d_{m,i} = \frac{e_{me,i}^{PP|CP}}{g_{me}} ; g_{me} = \max(\{e_{me,i}^{PP|CP}\})_{i \in I|J} \text{ (Eq. 12)}$$

353 
$$d_{r,i} = \frac{e_{mi,i}^{PP|CP}}{g_{mi}} ; g_{mi} = \max(\{e_{mi,i}^{PP|CP}\})_{i \in I|J} \text{ (Eq. 13)}$$

354 
$$\text{with } J = \{1, \dots, z\}$$

355 
$$d_{q,i} \geq d_{c,i}h \text{ (Eq. 14)}$$

356 
$$\text{with } q, c \in N ; q \neq c ; d_{c,i} = \max(\{d_{v,i}\})_{v \in N}$$

357

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

368

369 While simple in its formulation, our LGP approach is flexible to be expanded in multiple ways that  
370 are relevant for the study of the resource nexus. Such expansions can be included via the  
371 weightings, the goal definition or the constraints in a given LGP set-up, depending on the specific  
372 case. For example, the goals could be defined based on alternative criteria, such as resource  
373 availability, economic feasibility, policy targets, and/or planetary boundaries. The goals could  
374 also differ among countries and/or industries if desired. Alternative weightings can also be  
375 applied, and, to illustrate this, we use the following weightings as suggested by Oers and Tukker  
376 (2016): (1) ‘panel data’: according to expert judgment; (2) ‘distance-to-target’: deviations from  
377 2050 world boundaries; and (3) ‘shadow prices’: non-market prices (further information on the  
378 weightings is available in supporting formation S3). Other nexus aspects that can be included in  
379 optimization models are competing interests within environmental constraints (Leavesley et al.  
380 1996), as well as technical, capital capacity and demand limits (Zhang and Vesselinov 2016). The  
381 proposed nexus strength metric provides a simple representation of the relevant resource  
382 nexuses in the scope of the global economy. The practical relevance of this metric will however  
383 depend on specific local environmental, socio-economic and political conditions.

384

## 385 <heading level 1> Results

386

387 This section presents the GRN results according to the proposed nexus strength metric and for  
388 the five selected resources: water, energy, land, metals and minerals. The main results have been  
389 calculated using equal weights (each resource receives the same importance), and so the nexus

390 strength will relate solely to the absolute resource use. Also, the deviations have been calculated  
391 with respect to macroeconomic maxima (among all world industries). We thus speak of a strong  
392 nexus when the simultaneous use of at least two resources is significant with respect to the  
393 macroeconomic maximum resource use. Additional results using sector maxima, different  
394 weighting schemes ('distance-to-target', 'panel data', and 'shadow prices'), sensitivity of the  
395 threshold  $h$ , and normalized resource use (according to industrial output) are used for discussion  
396 purposes and can be found in supporting information S3 and S4. First, an overview of the GRN is  
397 presented. Then, at the industry level, the results from both the production perspective (i.e.  
398 nexus strength associated with each industry's production activity) and the consumption  
399 perspective (i.e. nexus strength caused by the final demand for each industry) are analyzed.  
400 Lastly, we present the country-level nexus strengths from the production perspective.

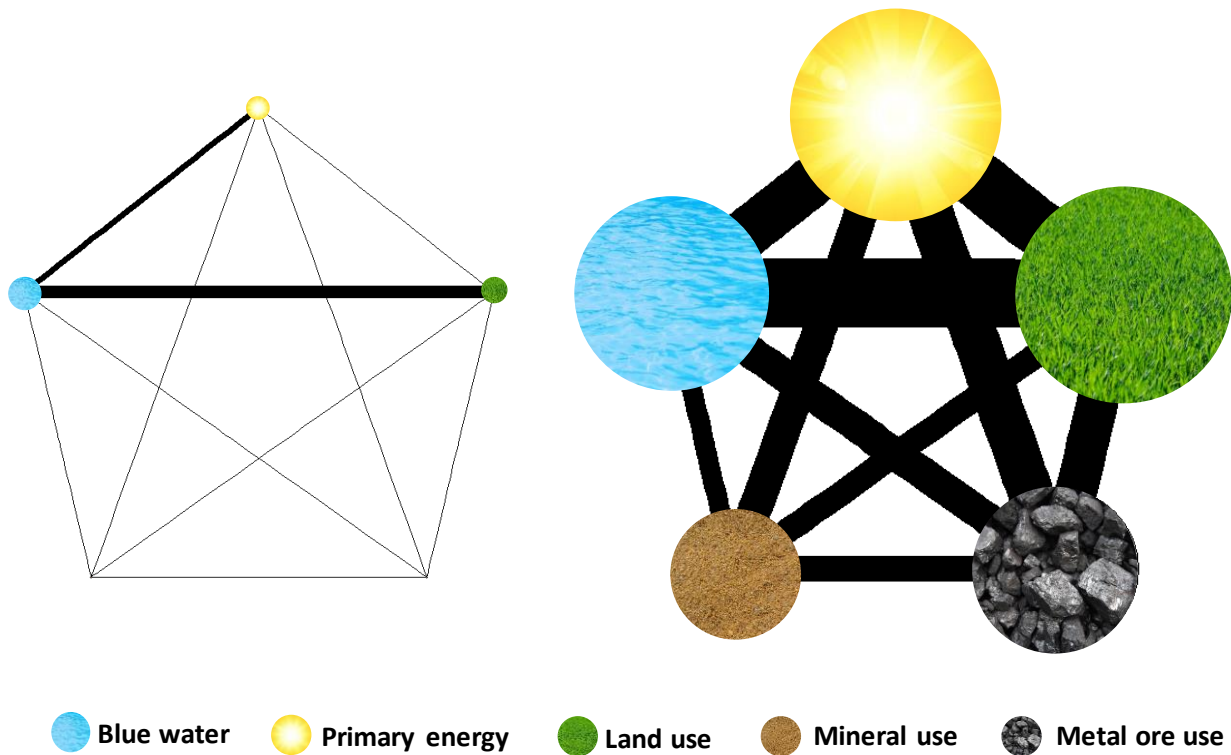
401

## 402 <heading level 2> Global overview of the nexus strength

403

404 An overview of the resource nexus for the global economy, corresponding to the aggregation of  
405 the nexus strength values of each country-specific industry (see equation 7), is presented in  
406 Figure 1. It merits noting that relatively more frequent resources (those which appear in a larger  
407 amount of nexus) will be overrepresented as all possible two-node combinations are considered,  
408 and so the individual contribution of each resource will be included in each combination. For  
409 example, a water-energy-land nexus will be broken into all possible two-node combinations:  
410 water-energy, water-land, and energy-land. If, let us assume, water has a high nexus strength,  
411 such strength will propagate to all water nexuses: water-energy and water-land. The proposed

412 visualization should thus be interpreted as a measure of the importance of two-node linkages,  
413 representing both the nexus strength and the frequency of the resources. For a measure of the  
414 nexus strength alone, we refer to the industry and product-level results presented later on this  
415 section. The visualization of the results is similar to the representation of relationships between  
416 resources by Andrews-Speed et al. (2014), yet instead of inputs and substitution possibilities, the  
417 edges and vertices (nodes connected by edges, as per graph theory) indicate the nexus strength.  
418  
419



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

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

427  
428 For industry nexuses (PBA or production perspective), we find important water-land and water-  
429 energy nexuses. The same combinations are important for product nexuses (CBA or consumption  
430 perspective), in addition to the energy-land and energy-metal ones. There is, however, a striking  
431 difference of the GRN strengths when viewed from the two perspectives – the strengths of the  
432 two-node nexuses appears much stronger for product nexuses. A plausible explanation relates  
433 to the threshold applied in the definition of the nexus. From a production perspective, primary  
434 and secondary industries are main users of natural resources across the world, and in many cases,  
435 a given industry has such a dominant role in the usage of a single resource that its usage of other  
436 resources become insignificant (i.e. below the  $h$  threshold in Eq. 14). For example, mining  
437 industries dominate the direct usage of metals or mineral ores across all economic activities.  
438 Their usage of other resources such as water and primary energy, however considerable in  
439 absolute values, become much less relevant concerning global resource security. Many resources  
440 thus fall below the proposed threshold of 1%, and the resource and/or the industry are excluded  
441 from the analysis as no nexus is identified. This hypothesis is confirmed by the fact that, when  
442 the threshold is lowered, the number of industries for which a nexus is identified increases more  
443 rapidly for industry nexuses than the product nexuses. For instance, a threshold of 1% yields a  
444 count of 3875 and 6660 nexuses according to the PBA and CBA approaches, respectively, whereas  
445 a value of 0.1% yields a count of 4580 (18% increase) and 6777 (2% increase), respectively. A  
446 more detailed look (see Figure S4.4 in supporting information S4) reveals that, for PBA nexuses,

447 changing the threshold affects mostly mining industries, although this change does not  
448 significantly alter the global nexus strength nor the role of neither minerals nor metals (see Figure  
449 S4.6). Moreover, product nexuses are made up by a larger amount of resources, and so the  
450 double-counting caused by considering any possible pair of resources will play a bigger role. The  
451 higher two-node nexus strengths measured for product nexuses also reflect complex networks  
452 involving multiple resources along supply chains of the finished products ultimately consumed.  
453 As such, our results indicate that the resource use and security concerns arising from the nexus  
454 are more crucial from a consumption perspective, i.e. the GRN is more critical regarding the  
455 provision of finished products and services than the production activities in general.

456

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

458

459 Following, the top 25 industry and product nexuses are presented in Figures 2 and 3, respectively.  
460 For industry nexuses, water-land and water-energy remain the strongest combinations. Among  
461 all the identified nexuses, energy (E) and water (W) are the most frequent nodes (present in 94%  
462 and 92% of nexuses, respectively), followed by land (L, 32%), minerals (Mi, 22%) and metals (Me,  
463 9%). This pattern suggests that the direct use of land, minerals, and metals are relatively  
464 concentrated while the consumption of primary energy and blue water are widely distributed  
465 across the industries. Out of a total of 22 configurations of at least two nodes identified, the most  
466 frequent configurations are W+E (50%) and W+E+L (18%). These results suggest that the current  
467 focus of the nexus research on combinations of water, energy and land (Bazilian et al. 2011), are



468 aligned with the most frequent combined direct resource use we identified in the context global  
469 economy.

470

471 In contrast to the industry nexuses, product nexuses are more complex and involve multiple  
472 nodes, such as the water-energy-land-metal-mineral and water-energy-land nexus (Figure 3).

473 Among all the identified nexuses, E and L are the most frequent nodes (both present in 98% of  
474 nexuses), followed by W (96%), Me (94%), and Mi (89%). Out of a total of 23 configurations of at  
475 least two nodes, the most frequent combinations are W+E+L+Me+Mi (86%) and W+E+L+Me (5%).

476 Also in contrast to the industry nexuses, we observe strong W+E nexuses, largely due to the role  
477 of coal electricity in supply chains in USA and China. Also, the strength of water nodes decreases  
478 with respect to industry nexuses, as its use, mostly focused in cultivation, is spread along supply  
479 chains (e.g., food services and biofuels). On the other hand, land nodes remain relatively stronger  
480 as its use remains concentrated in shorter supply chains of meat products.

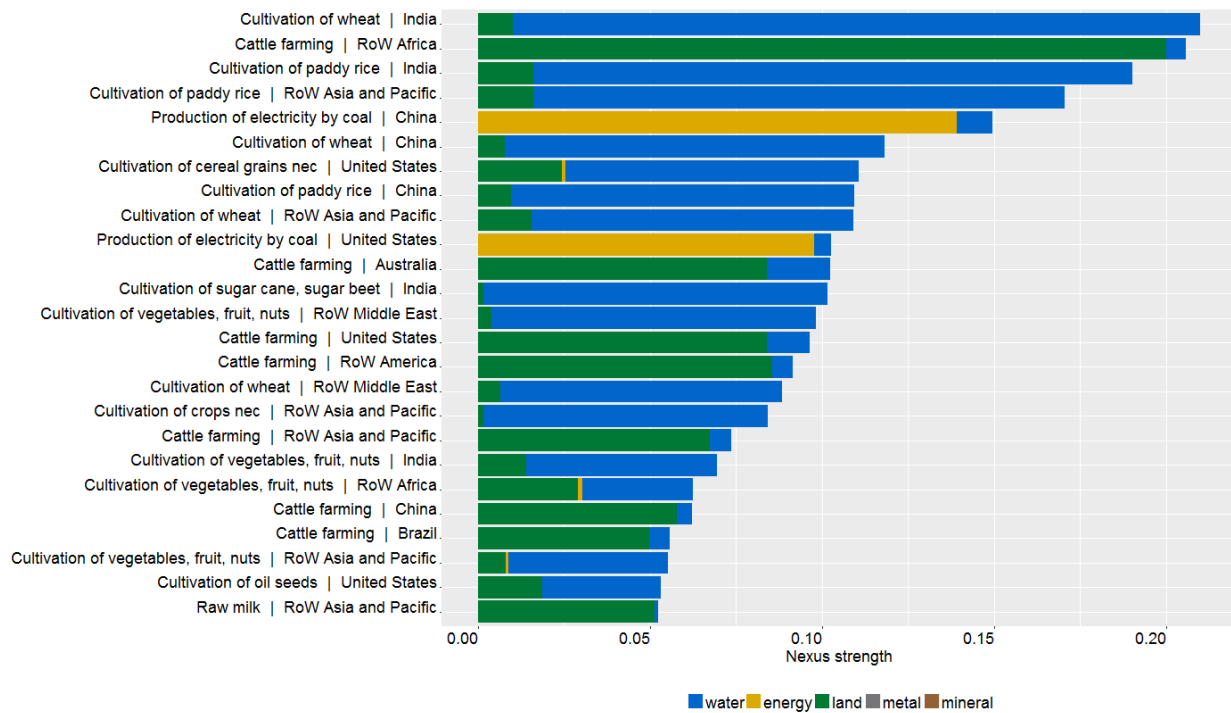
481

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

490 suggests that nexus issues may be minimized more effectively and in a more comprehensive  
 491 manner by targeting final demand categories.

492

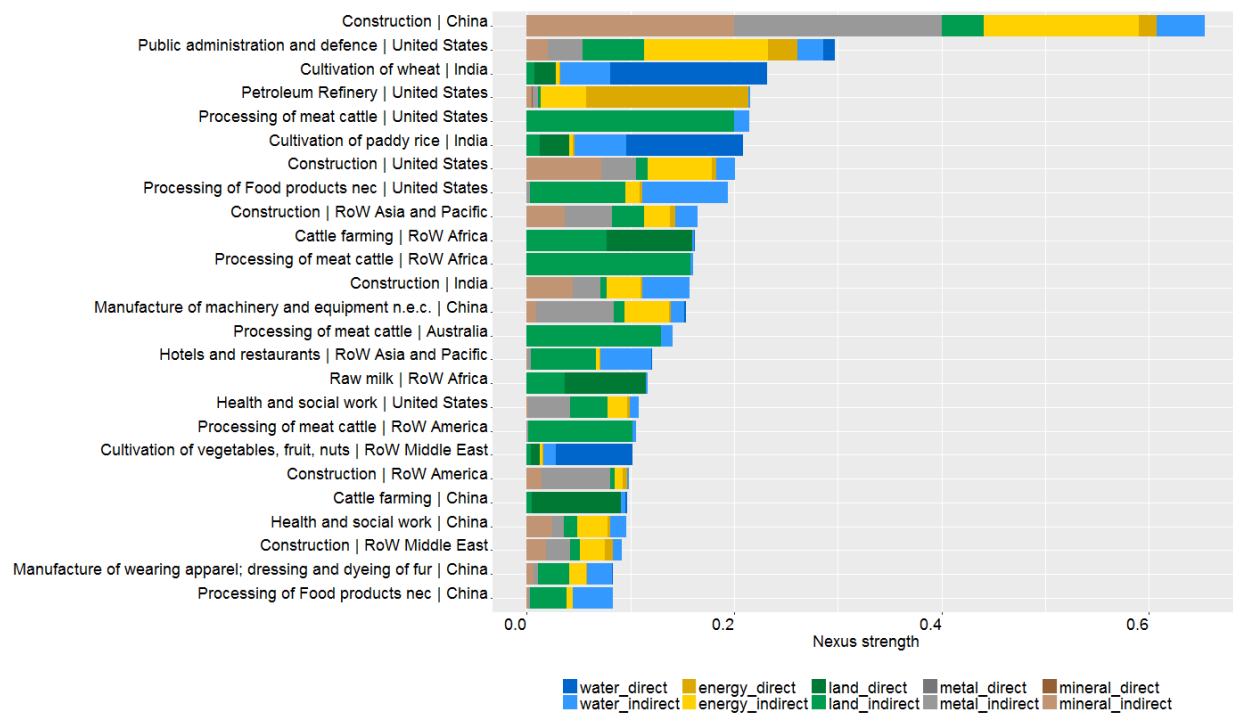
493



494

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

497



499

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

504

505 For industry nexuses, the most relevant one is the water-land nexus taking place in agricultural  
 506 activities. For crop cultivation activities, blue water consumption is the main driver of the nexus,  
 507 especially in wheat and rice production and due to their high water requirements. On the other  
 508 hand, land drives this nexus in animal farming activities, especially cattle farming, largely due to  
 509 the use of extensive management systems (Robinson et al. 2014). Another important nexus is  
 510 the water-energy nexus from coal power, which is driven by primary energy and where water is

511 used mostly for cooling purposes. Energy also plays a role in the water-energy-land nexus of crop  
512 cultivation activities such as cereal grains, vegetables, and fruits, largely due to high  
513 mechanization and the use of fossil fuels in the operation of agricultural machinery.

514  
515 For product nexuses, more complex nexuses are found, often including all five studied resources.

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

525

526 <heading level 3> Alternative specifications of the nexus strength

527

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

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

551

552 The nexus strength indicator is influenced by the weighting of the various nodes, and it is thus  
553 important to further analyze its effect on the results. To this end, we have defined three  
554 weighting schemes based on various criteria (expert opinion or 'panel data (PD)', distance to

555 planetary boundaries or ‘distance-to-target (DtT)’, and economic externalities or ‘shadow prices  
556 (SP)’ and re-calculated the nexus strength results accordingly (see supporting information S3 for  
557 the complete results). In general, the PD and DtT weightings illustrate the high importance of  
558 primary energy, while the SP weightings give land a notable importance. For industry nexuses,  
559 coal, gas and nuclear power gain positions in the top nexuses under the PD and DtT weightings  
560 via water-energy combinations, while agricultural activities monopolize the top nexuses via land-  
561 water combinations. For product nexuses, the PD and DtT weightings increase the importance of  
562 industries such as certain construction and manufacturing sectors, for which much energy is  
563 consumed in upstream activities; the SP weighting highlights the industries that rely on land-  
564 intensive supply chains, such as crop cultivation and food processing activities.

565

566 <heading level 2> Country-level nexus strength

567

568 The nexus strength by country and across the world are presented in Figure 4. The results  
569 correspond to the PBA approach (industry nexus) in order to reflect resource use taking place  
570 within national boundaries. The visualization approach is the same as that described in the  
571 section ‘Global overview of the nexus strength’ (see Figure 1). The country-level nexus strength  
572 values correspond to the aggregation of all the identified resource nexuses in a given country  
573 (see Figure 2 for the top industry-level nexuses). It is critical to note that the values of the vertices  
574 and edges have been scaled for visualization purposes only (relative values are maintained), and  
575 so these are shown proportionally bigger and wider, respectively. The same scaling factor is  
576 applied to all of the country-level values so that they are comparable among each other. Another

577 scaling factor, also different from the one used in Figure 1, has been applied for the world values  
578 for visualization purposes only. Only those countries with the strongest nexus are displayed in  
579 Figure 4, and we refer to supporting information S5 for the complete results for country-specific  
580 considerations. Overall, the nexus strength is relatively consistent with the levels of domestic  
581 output, with the top economies generally displaying the largest nexus strength values (as  
582 illustrated by the shade intensity in Figure 4). Across countries, the nexus profiles display a  
583 considerable diversity, largely due to differences in the economic structure, domestic policy,  
584 technology and resource endowments.

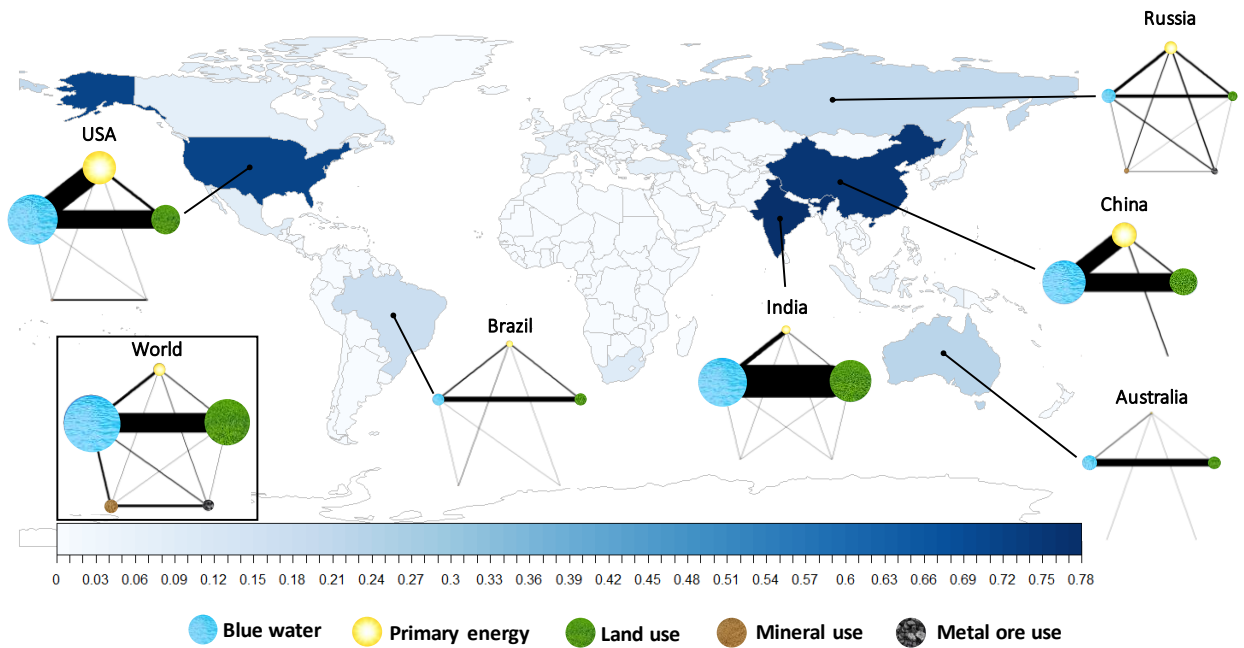
585 Consistent with the global pattern illustrated in Figure 1, the water-land nexus appears to be the  
586 strongest nexus combination. Largely associated with farming activities, this nexus is particularly  
587 strong in India, U.S.A., and China, where a large fraction of the land and water resources are  
588 located. The availability and quality of resource endowments, however, introduce nuances in the  
589 strength and composition of farming-related nexuses. For instance, the types of crops (e.g.,  
590 water-intensive such as rice or land-intensive such as grains), generally conditioned by local  
591 conditions but sometimes associated with domestic agriculture policies (see, for instance, the  
592 case of Northern China (Cai 2008)), also determine the relative importance of water and land in  
593 this nexus. The degree of mechanization and consequent use of fossil fuels in agriculture also  
594 induces energy-land and energy-water nexuses, for instance in the U.S.A. The second strongest  
595 nexus is the water-energy nexus from coal, gas and nuclear power industries, which is especially  
596 strong in the U.S.A. and China. These particular nexuses are well studied in the literature, and  
597 important drivers are the availability of coal/gas deposits and freshwater, domestic policy, and  
598 technology (Scott et al. 2011; Kahrl and Roland-Holst 2008). It also merits to highlight the

599 significant and less-studied metal-mineral nexus caused from some metal and mineral mining  
600 activities, such as copper mining in Africa and stone quarrying in the U.S.A., which is sometimes  
601 associated with the presence of 'accessory' metals and minerals (Scott et al. 2005). Some mining  
602 activities are also associated with a considerable water-mineral nexus, as freshwater is used for  
603 mineral processing and dust suppression (Mudd 2008).

604



605



606

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

613

614

615 <heading level 1> Conclusions

616

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

629 First, adopting a consumption perspective allows to account for resource use taking place at  
630 various steps of the supply chain, leading to the identification of stronger and more complex  
631 resource nexuses. Some industries/products may be more relevant for the resource nexus than  
632 previously thought, such as construction and service-based activities. This perspective, seemingly  
633 underutilized in the study of nexus issues, presents large potential to mitigate such issues, for  
634 instance via consumer-oriented policies that target specific nexuses (e.g. promoting diet changes  
635 to mitigate the water-energy nexus (Marrin 2014)). It merits noting that this perspective (as  
636 opposed to its production counterpart) ignores the spatial dimension, and so resource use need

637 not to take place in the same region. Indeed, resources become linked in the supply chain rather  
638 than in situ, and so this perspective offers complementary insights into combined resource use.  
639 To check whether multiple resources are being used in the same region, additional analyses  
640 should be conducted, such as structural path analysis (Peters and Hertwich 2006). Second, the  
641 consideration of multiple resources allows to identify nexus issues that may otherwise be  
642 overlooked using mainstream frameworks such as the water-energy-food nexus framework. For  
643 instance, the inclusion of metals and minerals suggests important metal-mineral, energy-metal,  
644 and water-mineral nexuses in both production and consumption perspectives. These insights  
645 open the doors to more comprehensive resource management practices leading to increased  
646 synergies and co-benefits. Regarding synergies, and in the context of sustainable consumption  
647 policies (e.g., EC (2008)), the five studied resources could be reduced simultaneously by fostering  
648 decreases in key final demand categories (e.g. meat products and construction activities).  
649 Regarding co-benefits, reductions in minerals (fertilizers) could be achieved in the context of  
650 land-water-food nexus policies in agriculture, for example by switching to crops that require less  
651 fertilizer (Weisler et al. 2001). Third, resource nexus issues differ greatly among countries, largely  
652 owing to output levels, economic structure, domestic policy, technology and resource  
653 endowments, and so nexus research could reveal different nodes of relevance for different  
654 countries and/or regions. Last but not least, the results also validate current research efforts at  
655 finer spatial scales, inasmuch as water, energy, and land present the strongest linkages globally  
656 both from a production and a consumption perspective.

657 This study is not without limitations, which can be described in terms of (1) LGP set-up, (2)  
658 indicators and (3) input-output (IO) methodology. First, our specific formulation is mostly focused

659 on the absolute use of resources, and thus overlooks other aspects relevant to the nexus debate,  
660 such as resource availability and prices. However, the proposed LGP approach is flexible to  
661 incorporate such aspects in the form of goals, weights and constraints. Such considerations will  
662 depend on a variety of factors, such as the scale of analysis and local conditions, but more  
663 generally on the specific nexus-related research questions addressed. Second, resource use alone  
664 does not necessarily align fully with the importance of a given nexus issue. For instance, blue  
665 water may be abundant in regions where it is used in large quantities, or the presence of  
666 pollutants in water may influence its efficiency and uses. For these reasons, the use of indicators  
667 that reflect resource scarcity (e.g. scarcity-weighted footprints (Lenzen et al. 2013)), economic  
668 feasibility and/or quality can provide a better understanding of the importance of nexus issues.  
669 For instance, considerations of scarcity could yield relevant metal-energy nexuses in the context  
670 of emerging renewable energy technologies (Hertwich et al. 2015). Similarly, considerations of  
671 quality could highlight relevant water-energy and water-metal nexuses, for instance associated  
672 with shale gas (Kharak et al. 2013) and mining activities, respectively. Also, the use of more  
673 detailed resource indicators as nexus nodes (e.g., specific metals and croplands) could shed  
674 additional insights into concrete issues at various scales. The third and last limitation relates to  
675 known methodological limitations of IO approaches (Miller and Blair 2009). For example,  
676 insufficient disaggregation and the use of monetary values can misestimate the importance of  
677 certain economic flows, such as water flows being undervalued due to inadequate pricing (Rogers  
678 et al. 2002). These limitations could be addressed, for instance, by using disaggregation of IOTs  
679 (Lenzen 2011) (e.g. through hybrid models) and physical input-output tables (Hubacek and Giljum

680 2003). Also, our approach does not capture trends as it uses a single year IO database, an issue  
681 that could be addressed by using existing time series.

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

687

## 688 Acknowledgements

689

690 The authors would like to thank Peter Berrill for his editing remarks, Arjan de Koning, Ester van  
691 der Voet, Sebastiaan Deetman, Angelica Mendoza Beltran and eight anonymous reviewers for  
692 their comments, and Luran van Oers for sharing valuable information.

693

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695

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