Locating pressures on water, energy and land resources across global supply chains

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Abstract

Measures which address the degradation and over-exploitation of natural resources are urgently needed, in individual countries and globally. However, the extraction and use of natural resources is highly interconnected, spatially and sectorally, within a complex web of interactions and feedbacks. Conventional resource footprinting does not reveal how pressures on natural resources are distributed across country and sector supply networks. Within this study pressures across the global water, energy and land (WEL) system are located within the supply networks of 189 countries and 24 global sectors. Pathways of water, energy and land use are found to be mainly indirect, arising from country and sector resource dependencies on immediate (Scope 2) and upstream (Scope 3) producers in their supply network. However, the distribution of these pressures is found to exhibit a high level of variation within and between national and sectoral supply networks and resource systems. Such differences in the resource pressure profile of countries and sectors is scarcely recognised by existing modelling approaches or supplier reporting guidelines, but is of major consequence for the study and management of pressures across the WEL system. If measures are not taken to extend accountability for the indirect pressures imposed across the WEL system, the resource burden of consumption will be greatly mismanaged.

Keywords: water-energy-land; resource security; sector supply chains; Scope 1-3; Production Layer Decomposition (PLD); MRIOA

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1. Introduction

The supply chains of goods and services rely on systems of production that are spatially disaggregated and organisationally complex (Bode & Wagner, 2015). As a result, the link between consumption decisions and their impact on the environment is often separated by a dense network of sectoral interdependencies with impacts occurring and interacting across different layers of production systems. This can implicate a sector’s direct operations, immediate suppliers and upstream suppliers - commonly termed ‘Scope 1’, ‘Scope 2’, and ‘Scope 3’ (Hertwich & Wood, 2018) - in its overall resource footprint. For example, a clothing retailer will use energy directly to operate its stores (Scope 1), but will also rely indirectly on resource use including energy in factories to manufacture its clothes (Scope 2) and, further upstream its supply chain, on water, land and energy for cotton farming to supply those manufacturers (Scope 3). Understanding how country and sector resource dependencies are distributed across their supply network is critical to pin-point where interventions to reduce their impact should be targeted.

Although instructive, the resource footprint of a country or sector does not reveal how its resource demand is imposed across its supply networks. This matters since the distribution of resource use across supply networks might vary between sectors, countries and environmental systems, demanding entirely different management approaches to ensure their sustainability. Figure 1 illustrates two cases where management of sectoral pressures across the water-energy-land system can demand either (i) interventions at a single level of a sector’s supply chain (Sector A) or (ii) a set of disparate interventions in upstream and downstream supply chains (Sector B). Mapping the profiles of resource use across supply chain networks reveals how water, energy and land resources can be managed in an integrated manner.
Figure 1. Profiles of resource use across supply networks

Schematic exemplifying different profiles of water, energy and land footprints in sector supply networks. Sector A illustrates a sector where water, energy and land use is concentrated at the same stage (Scope 2) of its supply network, implying potential for combined resource management at such level. Sector B illustrates a sector with different supply chain profiles of water, energy and land use, creating misaligned management priorities which demand multiple interventions upstream and downstream its supply network.
Production Layer Decomposition (PLD) has emerged as a disciplined approach to examine how the environmental burden of countries and sectors is concentrated within their supply networks (Lenzen et al., 2007). Using data on sectoral interdependencies, described in Section 2, PLD enables the unravelling of the supply chain of consumption activity (e.g., linked to global, national or sectoral demand) to assess its production requirements and associated environmental impacts at different stages of its ‘production tree’ (Kitzes, 2013).

To date, the application of PLD has mostly been levelled at assessment of carbon emissions through sectoral supply chains (cf Rodriguez-Alloza et al., 2015; Schmidt et al., 2019; Lenzen et al., 2018; Kucukvar & Samadi, 2015; Hertwich & Wood, 2018). Policy developments around environmental impact assessment of sectors have also been more heavily focused on carbon emissions accounting, reflected in the development of reporting protocols to assess companies Scope 1, 2 and 3 footprint (Farsan et al., 2018; Redevco, 2019; Richards, 2018). Meanwhile, the application of PLD to water, energy and land use is limited to only a few studies. Lenzen et al. (2012) evaluates the contribution of production layers to water footprints and high risk water footprints across major global regions, but does not analyse their significance at a sectoral level. However, Guan et al. (2019) performs a detailed PLD of water, energy and land use pathways for China. For energy-related footprinting, PLD has been used more widely, but its applications have been limited to case studies of specific sectors (cf Heihsel et al., 2019; Malik et al., 2016; Lenzen, 2008) or regions (Veiga et al., 2018). For land, no cross-country applications of PLD were found at the time of writing. Accordingly, there is a clear need to understand how water, energy and land use and risk is distributed across national and sectoral supply networks.
By decomposing water, energy and land use across country and sector supply chains, this study examines:

1. how water, energy and land use is distributed across Scope 1, Scope 2 and Scope 3;
2. priorities for integrated management of water, energy and land use across 24 global sectors; and
3. the effects of truncating resource assessment to Scope 1 and Scope 2.

Section 2 outlines how resource use and resource risk across the WEL system can be evaluated via decomposition of national and sectoral supply networks. The findings of this analysis, reported in sections 4 and 5, convey the importance of different supply chain scopes for integrated management of pressures across the WEL system. Section 6 comments on the significance and limitations of these findings and their implications for future research on and management of the global WEL system.

2. Data and Methods

This section outlines how PLD is applied to the assessment of country and sector resource pressures across the WEL system. Quantitatively, PLD of a country or sector’s resource footprint, $F$, is achieved by expressing the Leontief demand-pull equation $F = fL_y$, well documented elsewhere (cf. Miller & Blair, 2009; Kitzes, 2013; Kanemoto et al., 2012), as a set of power terms corresponding to subsequent production levels $i$ and their associated resource use $F_i$:

$$F = F_1 + F_2 + F_3 + ... = fy[I + fyA + fyAA + ... = fy[I + A + A^2 + ...] \quad (1)$$

where $F$ refers to a total resource intensity vector, $y$ refers to a given level of final demand, and $A$ refers to the technical coefficients matrix describing sectoral interdependencies.
Since all values in the $A$ matrix are below 1, the power series converges to zero as the number of production levels $n$ increase. This step-wise calculation can be used to evaluate the overall water, energy and land footprint of countries and sectors at different stages of their supply network. This calculation is typically truncated to a level (i.e. supply chain scope) which captures the majority of a country or sectors resource footprint. Within this assessment, 11 production levels (i.e. direct and 10 indirect tiers of the supply network) are examined which capture on average $>95\%$ of overall water, energy and land use within countries and sectors.

PLD is also applied to examine where sources of resource insecurity originate in country and sector supply networks by measuring high risk water, energy and land use at each production level. A mask vector (of ones and zeros) was used to filter high, medium and low risk production and associated resource use driven by countries as sectors, as follows:

$$f_c = \begin{cases} 0, & R I_c \geq \frac{R I_{\text{max},i} - R I_{\text{max},i-1}}{3} \\ 1, & \frac{R I_{\text{max},i-1}}{3} \leq R I_c \leq \frac{R I_{\text{max},i}}{3} \end{cases}$$ (2)

where $f_c$ is a ‘mask’ value of ‘0’ or ‘1’ to assign the production of a country, $c$ to a given risk category; $i$ is a given risk category (high=3, medium=2, low=1), which can be adjusted to change the level and number of risk categories used to filter national and sector resource footprints; and $R I$ is the raw index value data for a country, $c$. Due to the lack sector-specific resource risk data available, it is assumed that sectors experience the same level of resource risk as indicated by country risk indices summarised in Table 1.
| Resource          | Measure                                                                 | Units | Resolution | Date | Source                        |
|-------------------|--------------------------------------------------------------------------|-------|------------|------|-------------------------------|
| Water Footprint   | Agricultural and industrial blue water use (from groundwater and aquifers) and green water use (precipitation and evapo-transpiration) | m³    | Sector     | 2005 | WaterStat 2019 (Hoekstra et al., 2011) |
|                   |                                                                          |       |            |      |                               |
| Water Risk Footprint | Projected blue water scarcity under a near-term (2020) business-as-usual climate scenario | m³    | Country    | 2010 | WRI 2015                      |
|                   |                                                                          |       |            |      |                               |
| Energy Footprint  | Energy use from natural gas, coal, petroleum, nuclear, hydroelectric, geothermal, wind, solar, tide, wave, biomass, and waste | J     | Sector     | 2015 | IEA 2019                      |
|                   |                                                                          |       |            |      |                               |
| Energy Risk Footprint | Energy insecurity based on domestic self-sufficiency, reliability of energy infrastructure, and ability of energy providers to meet current and future demand. | J     | Country    | 2018 | World Energy Council 2018     |
| Land Footprint    | Agricultural land use area reported for 172 crops.                      | ha    | Sector     | 2015 | FAO 2019                      |
|                   |                                                                          |       |            |      |                               |
| Land Risk Footprint | Index of sustainable nitrogen management based on nitrogen use efficiency and land use efficiency | ha    | Country    | 2010 | Yale University 2019          |
For the purpose of cross-sectoral comparison at a global scale, an aggregated version of the Eora (2019) database which distinguishes 24 major sectors for each country is used because this is the level at which data exists for all countries. However, for PLD of Country resource footprints, the full Eora (2019) database is used for improved reliability. The caveats associated with using a lower resolution version of the Eora (2019) database are discussed in Section 6.

3. Analysis

The PLDs of water, energy and land footprints are analysed from national and sectoral perspectives in Sections 4 and 5. Section 4 presents the contribution of Scope 1, 2 and 3 production levels to country resource footprints and high risk resource use across the WEL system. Section 5 describes how water, energy and land pressures are distributed across major global sectors and highlights the significance of Scope 1, 2 and 3 production within this context. All data relating to analysis within this study is available from Taherzadeh (2020).

4. Supply chain profile of national resource footprints

Since environmental footprinting is commonly undertaken at an economy-wide scale, it is pertinent to ask how far down national supply networks we need to go to capture effectively and manage the environmental burden of a country’s consumption. Although this question has been explored within the context of national carbon emissions, the supply chain scope of national water, energy or land footprints is poorly understood. By evaluating national water, energy and land footprints from a supply-chain perspective, this section highlights the contribution and relative importance of upstream and downstream suppliers to pressures across the WEL system. The significance of different production levels in national supply networks to their resource footprint reflects several factors, including *inter alia* the sectoral composition of national consumption, the complexity of sector supply chains, the resource intensities of production processes, and the geographical specificity of resource risks. These factors vary by country
and across different dimensions of the WEL system resulting in differences in the contribution of production levels to national resource footprints.

Figure 2 illustrates the primacy of different production levels and supply chain scopes to national water, energy and land footprints across the 189 countries analysed. Within the majority of countries Scope 3 suppliers contribute more greatly than Scope 1 or Scope 2 suppliers to national water footprints \( n = 121 \), energy footprints \( n = 163 \) and land footprints \( n = 143 \), as indicated by the pink shading of countries in Figure 2. The importance of Scope 3 resource use is also substantiated by its high contribution among the top 5 countries with the largest water footprints (median = 35.4%, mean = 45.3%), energy footprints (median = 64.5%, mean = 59.4%) and land footprints (median = 34.7%, mean = 46%) which identified within this analysis. Moreover, as shown in Figure 3, Scope 3 suppliers are also the primary source of national high risk water use \( n = 168 \), high risk energy use \( n = 150 \), and high risk land use \( n = 186 \).

Nevertheless, country variation between the profiles of national resource footprints across supply networks is evident, as shown by the cross-section of country case studies in Figures 2 and 3. For example, direct production accounts for around 50% of Russia’s water and land footprint, but only 19.1% of its energy footprint which is concentrated further upstream its supply network in Scope 2 (39%) and Scope 3 (41.9%); a similar picture is seen in China. In contrast, for other countries, such as the UK, USA, South Africa and Australia, less than 5% of their water, energy and land footprints is imposed in Scope 1 of their supply network, and between two-thirds and three-quarters is concentrated in Scope 3.

Figure 4 presents a series of box plots capturing variation in the contribution of Scope 1, Scope 2 and Scope 3 production levels to national water, energy and land footprints, and the contribution of high risk water, energy and land use sources in 189 countries.
Figure 2. Contribution of Scope 1-3 suppliers to national WEL footprints

Choropleth map illustrating the supply chain scope (1-3) of primary importance to national water, energy and land footprints. Country colouration is based on which supply chain scope (1-3) accounts for the largest share (i.e. more than 33.3%) of its resource footprint. Full production layer decomposition results for a cross-section of countries based on geographical coverage and largest overall resource footprint.
Figure 3. Contribution of Scope 1-3 suppliers to national WEL risks

Choropleth map illustrating the supply chain scope (1-3) of primary importance to national high risk water, energy and land footprints. Country colouration is based on which supply chain scope (1-3) accounts for the largest share (i.e. more than 33.3%) of its high risk resource footprint. Full production layer decomposition results for a cross-section of countries based on geographical coverage and largest overall high risk resource footprint.
Figure 4. Distribution of Scope 1-3 production embodied in national WEL pressures
Box plot illustrating the contribution (%) of Scope 1, Scope 2 and Scope 3 suppliers to national water (blue), energy (purple) and land (green) footprints (top) and national high risk water, energy and land use (bottom). Box plots represent inter-quartile range; mean values = dashed lines; median values = solid lines.
This cross-cutting analysis reveals several qualities about the supply chain scope of national pressures across the global WEL system. First, on average, direct (or Scope 1) production accounts for between 5% and 20% of the overall resource demand of countries across the WEL system. Second, Scope 3 production (upstream suppliers) contributes on average more than both Scope 2 (direct suppliers) and Scope 1 within this context. Even when aggregated, Scope 1 and Scope 2 suppliers account for between 40-50% of total national water, energy and land footprints. Third, the contribution of Scope 2 production to national resource footprints varies between different dimensions of the WEL system. Lastly, the burden of national consumption on high risk water, energy and land resources occurs further upstream their supply networks (in Scope 3) than overall resource demand across these systems (Figure 4).

The importance of Scope 2 and 3 production is underlined by their contribution to pressures of global consumption across the WEL system in absolute terms, illustrated in Tables 2 and 3. However, the heterogeneity of supply profiles for national resource footprints also operates at a sectoral scale, demanding the decomposition of supply networks for water, energy and land use by specific consumption activities.

Although highly significant to national water, energy and land footprints, Scope 3 resource use accounts for a total of eight levels (3-10) of their supply network so implicates a large number of suppliers. Disaggregating Scope 3 production helps to identify the most significant production level contributing to national pressures across the WEL system, when Scope 3 production levels are treated assess as eight discrete production levels. On average, production layer two (i.e. Scope 2) is the most significant source of national pressure on global water, energy and land resources. However, the significance of production levels in relation to national dependence on high-risk resources varies across the WEL system. Direct production is the greatest source of high risk energy use. However, Scope 2 suppliers account for the greatest source of high risk water and land use.
Table. 2. Contribution of Scope 1-3 resource use to global resource footprints

|                  | Global Water Footprint (% Total) | Global Energy Footprint (% Total) | Global Land Footprint (% Total) |
|------------------|----------------------------------|----------------------------------|---------------------------------|
| **Scope 1**      | 1.32 Tm³ (13.9%)                 | 54.9 EJ (11.7%)                  | 0.493 Gha (15.9%)              |
| **Scope 2**      | 3.36 Tm³ (35.4%)                 | 131 EJ (27.8%)                   | 1.07 Gha (34.6%)               |
| **Scope 3**      | 4.80 Tm³ (60.6%)                 | 285 EJ (60.6%)                   | 1.53 Gha (49.5%)               |

Table. 3. Contribution of Scope 1-3 resource use to global resource risk

|                  | Global High Risk Water Footprint (% Total) | Global High Risk Energy Footprint (% Total) | Global High Risk Land Footprint (% Total) |
|------------------|-------------------------------------------|-------------------------------------------|------------------------------------------|
| **Scope 1**      | 0.171 Tm³ (8.6%)                          | 5.89 EJ (32.3%)                          | 35Mha (3.3%)                            |
| **Scope 2**      | 1.01 Tm³ (50.5%)                          | 5.06 EJ (27.8%)                          | 302Mha (28.1%)                         |
| **Scope 3**      | 8.18 Tm³ (41%)                            | 7.26 EJ (40%)                            | 740Mha (68.7%)                         |

5. Supply chain profile of sectoral resource footprints

The supply chain profile of water, energy and land use exhibits a high level of variation within and between sectors. Intra-sectoral variation between the supply chain profile of water, energy and land use implies the presence of multiple ‘hotspots’ for resource management and the absence of a single ‘sweet-spot’ (i.e. production level) where these pressures can be managed in an integrated way across supply networks. Meanwhile, intra-sectoral variation in the supply chain profile of water, energy and land use suggests the need for different management priorities between sectors in order to reduce pressures across the entire WEL system.

Figure 5 summarises the distribution of water, energy and land use (solid lines) and high risk water, energy and land use (hatched lines) across 24 global sectors. These profiles are derived from aggregating the absolute resource use embodied in the production layer of each sector across 189 countries in the [Eora](https://www.eora.com) database. The Agriculture sector is a suitable entry point for discussing this analysis given the importance assigned to agricultural production in resource assessment. Unsurprisingly, around 80% of water and land use (and high
risk water and land use) in the *Agriculture* sector is direct, in Scope 1 of agricultural supply chains (Figure 5.1). However, only 21% of the energy footprint and 36% of the high risk energy footprint of the *Agriculture* sector is due to its direct energy use. As Figure 5.1 shows, the energy footprint of the *Agriculture* sector is distributed across more supply chain stages (around 7) than its water and land footprint (around 3). In contrast, the profile of water, energy and land footprints across the *Food and Beverages* sector exhibit high correlation, with WEL impacts concentrated in Scope 2 of its supply network (Figure 5.4). Strong alignment between the supply chain profile of water, energy and land use is also seen in several other sectors, including *Textiles and Apparel* (Figure 5.5), *Wood and Paper* (Figure 5.6), and *Construction* (Figure 5.14). However, for the majority of sectors, a mismatch between the concentration of single or multiple aspects of resource use and resource risk for water, energy and land across global production networks is observable (see Figure 5). For example, direct resource use accounts for the large contribution to energy footprints in *Electricity, Gas and Water* (Figure 5.13), *Transport* (Figure 5.19), *Mining and Quarrying* (Figure 5.3), and *Petroleum and Mineral products* (Figure 5.7) sectors but an insignificant proportion of water and land footprints.

In contrast, resource use in some sectors are highly diffuse across their production networks - see *Metal Products* (Figure 5.8), *Electrical and Machinery* (Figure 5.9), *Transport Equipment* (Figure 5.10), and *Other Manufacturing sectors* (Figure 5.11). Within these sectors, no clear potential for straightforward management of water, energy and land resources is seen. Moreover, even where sectoral resource use is concentrated within a specific level of its production network, this scope rarely accounts for its total resource burden which is distributed across other individually less important, but collectively significant production levels.
Figure. 5. Supply network decomposition of WEL pressures in major global sectors

Series of plots illustrating the contribution of different production layers (z-axis) to the water, energy and land footprints (y-axis) of 24 global sectors.
When considered within the context of sectoral supply chain scopes, the major contribution of Scope 2 and Scope 3 pressures on water, energy and land resources is seen more clearly. Figure 6 presents a disaggregation of resource use and resource risk imposed by global sectors across the WEL system in relation to Scope 1, Scope 2 and Scope 3 suppliers. The contribution of Scope 1 production to water, energy and land use embodied in supply chains varies between sector. Moreover, the significance of Scope 1 production also varies between water, energy and land resource footprints.

On average, Scope 1 production contributes most towards sectoral energy footprints (median = 14.9%, mean = 22.7%) and high risk energy use (median = 12.2%, mean = 23.5%) and it contributes least towards sectoral land footprints (median = <1%, mean = 7%) and its responsibility for high risk land use is also small (median = 0%, mean = 5.7%). The contribution of Scope 1 production to sectoral land footprints is similar to that for sectoral water footprints (median = 1.7%, mean = 9.1%) due to their coupled nature. However, Scope 1 production accounts for a higher proportion of sectoral high risk water use (median = 7.9%, mean = 17.4%) than high risk land use. Scope 2 production accounts for a more significant source of sectoral energy footprints in 18 of the 24 sectors analysed.

More broadly, Scope 2 production is found to be a greater source of resource pressures or risk across WEL resources than Scope 1 production in 16 of the 24 sectors modelled. However, Scope 3 production is found to account for a greater proportion of sectoral resource pressures than Scope 2 production in most sectors, as illustrated in Figure 5.
Figure 6. Contribution of Scope 1-3 suppliers to sectoral resource footprints.

Series of polar charts illustrating the contribution of Scope 1, Scope 2 and Scope 3 production to sectoral resource footprints (top) and high risk resource footprints (bottom). Numbers on radial axes correspond to sectors in key.
Scope 3 production is a particularly significant source of sectoral land footprints (median = 74.5%, mean = 67.6%), high risk land use (median = 83.3%, mean = 74.1%), water footprints (median = 76.7%, mean = 68.5%), high risk water use (median = 63.9%, mean = 55.6%), energy footprints (median = 48.7%, mean = 45.6%) and is also responsible for high risk energy use (median = 45.9%, mean = 42.2%). Consequently, truncating resource assessment across the WEL system to only Scope 1 (i.e. direct) and Scope 2 (immediate suppliers) overlooks a potentially large share of sectoral water, energy and land resource use.

6. Discussion

Globalisation, outsourcing and subcontracting of production processes have led to an expansion in the supply networks of countries and sectors (Maluck & Donner, 2015). As a result, dependence on a remote suppliers (i.e. suppliers of suppliers) within global production and consumption systems has grown (Blackhurst et al., 2011). Despite their growing significance, businesses often have limited understanding of the regulatory, environmental, and social context of their upstream suppliers (Scope 3), when compared with their own operations (Scope 1) and those of their immediate suppliers (Scope 2) (O’Rourke, 2014). Limited knowledge of Scope 3 suppliers, has created an enabling environment for social and environmental exploitation in supply networks due to their de facto autonomy from arm-lengths relationships with final consumers (Blanchard, 2015). This has been seen in several recent cases, most notably the horsemeat scandal in the UK involving the adulteration of meat supply by Scope 3 suppliers of supermarkets (Abbots & Coles, 2013); reports of labour exploitation in agricultural supply chains (Whewell, 2019); and deforestation in tropical areas to satisfy consumption for animal feed, timber and palm oil (Lambin et al., 2014).

Identifying opportunities for integrated management of country and sector pressures across the WEL system relies on an understanding of where water, energy and land resource use is concentrated throughout global supply chains.
By decomposing the water, energy and land footprints of countries and sectors across supply chain layers, this study reveals the contribution of direct suppliers (Scope 1), immediate suppliers (Scope 2), and upstream suppliers (Scope 3) to national and sectoral resource pressures across the WEL system. By unravelling the full supply chains of national and sectoral consumption, this study makes a foundational contribution to the understanding of how water, energy and land use is distributed throughout globalised systems of production and trade.

A supply chain perspective of the WEL system reveals several important features of national and sectoral resource use. First, water, energy and land use are distributed unevenly across country and sector supply networks, therefore concentrating their resource demand within particular production layers. Second, the link between consumption decisions and their impact on water, energy and land resources is mostly indirect, beyond the operational scope of sectors. Third, within supply networks, upstream suppliers (Scope 3) are responsible for the majority of national and sectoral pressures on water, energy and land resources. Fourth, the distribution of water, energy and land use exhibits large variation within and between sectors. These findings reveal both challenges and opportunities to the integrated and sustainable management of pressures across the WEL system. The apparent heterogeneity of water, energy and land use within national and sectoral supply networks suggests that there is no one-size fits all approach or single intervention point capable of mitigating pressures across these systems. Instead, resource management must be tailored to reflect the unique profiles of water, energy and land use pressures arising from country and sector consumption. Critically, this analysis draws into question the relational nature of water, energy and land use which underpins the nexus concept. Although water and land use appear closely coupled in global supply networks (see Figure 5), the use of high risk water and land resources, water and energy resources, and land and energy resources are largely independent when viewed from a supply-chain perspective.

Despite the complexity of water, energy and land use profiles in global supply networks, this assessment highlights several avenues for more effective assess-
ment and management of country and sector pressures across the WEL system. First, extending the coverage of resource footprinting to Scope 3 stands to highlight major sources of country and sector resource use. Such potential for assessment is rarely prescribed within current national and corporate reporting guidelines which limit resource accounting of national and sectoral consumption to Scope 2 (first-level suppliers) (Richards, 2018). Accordingly, changes to such guidelines to encourage more comprehensive coverage of Scope 3 suppliers would help to improve the utility of resource accounting exercises. Second, as demonstrated within this study, mainstreaming the use of PLD within country and sector resource footprinting can help to guide research and policy priorities for integrated natural resource management. Third, a priori treatment of water, energy and land systems in an integrated manner might inspire management interventions with sub-optimal outcomes for their sustainable management where the pressures on these systems originate at different stages of national and sectoral supply chains. As such, resource management must recognise and accommodate the different ways in which sectors use natural resources in their supply chain.

Further disaggregation of global supply chain relationships is needed to identify the specific supply chain pathways, actors, and production activities underpinning the resource burden of countries and sectors. Structural Path Analysis (SPA) is an advanced IOA technique which involves unpicking and ranking individual suppliers by their contribution to the environmental impact of countries or sectors in order to identify critical resource use paths in supply networks (Lenzen & Murray, 2010; Wood & Lenzen, 2009). For example, Owen et al. (2018) use SPA to identify important supply chain pathways relating to the UK’s demand for water, energy and food; Vivanco et al. (2018) use SPA to identify the contribution of direct (on-site use), dependent (one-way supply chains), and interdependent (supply-chain feedbacks, or nexus linkages) to the water and energy footprint of the United States and China; and Guan et al. (2019) use SPA to examine critical water, energy and land use pathways in China. Although potentially instructive, undertaking a SPA of resource use and risk pathways
for the entire global WEL system was out of the scope of this study.

The findings of this study must be understood within the data and methodological limitations of MRIO data and analysis. This study relies on two main data sources, (i) national economic and environmental accounts, reported according to the UN System of Economic and Environmental Accounting (UN 2014), and (ii) resource risk accounts.

Economic and environmental accounts form the underlying basis of MRIOA, but only capture reported activities within the economy and therefore overlook the environmental burden of unreported activities residing in the informal economy (e.g. land clearing for agriculture, biomass burning for energy and groundwater extraction), within supply chains (e.g. efficiency losses, illegal pollution, and spoilage), and post consumption (e.g. landfill waste, burning of gasoline in cars, and littering) (Kitzes 2013). As a result, these accounts do not capture the total environmental burden of human activity. Moreover, economic and environmental data accounts which are formally reported are prone to miscalculation due to spurious accounting at the national level based on poor sampling methods or deliberate misreporting (Akimoto et al. 2006; Marland 2008). The significant time cost involved in compiling MRIO databases creates a time-lag before they become available which demands that assessments of country and sector resource use have to be based on a snapshot of previous trade relationships, environmental production efficiencies, technological requirements, production recipes, and sectoral demand which might not reflect current conditions (Kitzes 2013). Bridging this time-lag is essential to ensure the relevance of MRIOA analysis to research and policy communities. The data underlying resource risk accounts used within this study are similarly besieged by their lack of coverage of activities, sectors and countries responsible for environmental degradation, as well as their reliance on poor quality data. Although resource risk data exists at a higher spatial resolution for water (cf Xu et al. 2019; Masud et al. 2019; Pfister et al. 2020; Quinteiro et al. 2018; Hoekstra et al. 2012), energy (cf BEIS 2018; Faturay et al. 2020), and land resource use (cf Godar et al. 2015; Godar & Gardner 2019; Croft et al. 2018), these cannot...
feasibly be linked to economic accounts due to the limited sub-national detail of MRIO tables (Wiedmann & Lenzen, 2018).

A central assumption of MRIOA is that expenditure between countries and sectors is a suitable proxy for the physical flows of goods, services and related resource dependencies between them. Due to the incomplete nature of physical environmental and commodity accounts at the same coverage of MRIO data, this relationship can only be interrogated within the context of simple commodity supply chains, and not the complex networks of resource use driven by countries and sectors within this study. Such indeterminancy casts doubt on the reliability of MRIOA to accurately assess the physical burden countries and sectors impose on water, energy and land resources. As Wynne (1992) notes, indeterminancy ‘exists in the open-ended question of whether knowledge is adapted to fit the mismatched realities of application situations’. This is pertinent to MRIOA as well as the burgeoning application of the nexus concept to understand and manage pressures across the WEL system. Nevertheless, the inadequacies of physical commodity accounts illustrate why this study necessitates the use of MRIOA.

Another source of indeterminacy relating to MRIOA pertains to the normative nature of consumption-based accounting which, unless modified (cf Andrew & Forgie, 2008; Lenzen et al., 2007; Peters, 2008), assigns full responsibility of upstream production and its associated resource burden to final consumption sectors and their territories. Indeed, some have questioned whether such attribution is fair given the distance of Scope 3 producers and decisions from downstream consumers (Afionis et al., 2017; Schmidt et al., 2019; Wiedmann & Barrett, 2013). Within this context, the extent to which production regimes emerge from downstream consumption decisions is poorly understood and calls into question whether the latter really ‘drives’ the former. Deep uncertainties also exist in our understanding of risk as it relates to the WEL system and the activities it supports. Resource risks are subjective and the factors that mediate their effects on different actors (e.g. individuals, households, sectors or countries) cannot be fully comprehended. Moreover, the notion that resource risks
are capable of being transmitted through supply chains, to final consumers (e.g. countries, sectors or consumers) relies on *a priori* assumptions about power sharing in the world economy. Further study of these dynamics if necessary in order to fully understand the actors and activities implicated in resource depletion upstream supply chains.

In addition to the methodological and data limitations which surround environmentally extended MRIOA and the risk-based resource footprinting approach developed here, additional caveats surround this study’s analysis. These concern (i) the categorisation of production layers, (ii) the use of sectoral data at a lower resolution and (iii) potential cross-country variation in the supply chain profile of water, energy and land footprints within national sectors. The aggregation of supplier contributions to resource use across levels 3-10 of country and sector supply into Scope 3 confounds a large proportion of economic and environmental activity. Where appropriate, the significance of specific production layers in Scope 3 is made explicit (see Figure 5, Section 4).

The use of MRIO data at lower resolution in order to construct 24 globally consistent sectors invariably reduces the accuracy of resource footprint analysis due to the conflation of resource use multipliers within their sub-sectors (Zhang et al., 2019). Improving the resolution of global sectoral analysis relies on improvements in the breadth of national economic and environmental accounting. Within this context, use of other MRIO databases, such as Exiobase (Wood et al., 2014), the Global Trade Analysis Project (GTAP) (Peters et al., 2011), and the World Input-Output Database (WIOD) (Dietzenbacher et al., 2013), which offer symmetric national input-output tables for a larger number of sectors (although for a smaller number of countries/regions) could help to improve the sectoral scope and policy relevance of analysis featured in this study. Lastly, the construction of global sectors disguises the unique supply chain profile of resource footprints in their national counterparts. Larger economies will also have a greater influence on this overall picture owing to their higher levels of sectoral consumption when compared to the global average. However, interpretation of PLD assessment for each country’s sector would involve 18144 (24 sectors × 189...
countries x 6 resource use indicators) observations which is out of the scope of assessment. It would also distract from the overall focus of the assessment to identify, at a high-level, sectoral differences between the distribution of resource use within and between economic sectors. Nevertheless, the extent to which PLD of resource use for global sectors can be generalised to a country context is ripe for case study analysis.

The findings of this study invite a refocusing of natural resource management around upstream suppliers, indirect resource consumption and recognition of the distinct profiles of water, energy and land use across country and sector supply networks. Although measures are being taken to improve reporting and regulation of Scope 3 impacts of sectors on greenhouse gas emissions (cf. Redevo, 2019; Farsan et al., 2018; Richards, 2018), this assessment highlights the need to extend this agenda to water, energy and land resources.

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