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

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ABSTRACT

Hotspots of resource use in country and sector supply chains are poorly understood, due in part to the unitary nature of environmental footprinting assessment. Understanding the profile of country and sector resource dependencies across their entire supply chain is needed to inform their integrated management. Within this study pressures across the global water, energy and land (WEL) system are located along the supply networks of 189 countries and 24 global sectors. These profiles reveal the focal supply chain tier(s) where country and sector pressures across the global WEL system arise. Viewed through a supply chain lens, pathways of water, energy and land use are found to be mainly indirect, arising from country and sector resource dependencies on immediate (tier two) and upstream (tier three+) producers in their supply network. However, the distribution of these pressures varies within and between national and sectoral supply networks and resource systems, requiring tailored management to mitigate their multiple impacts. These 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 to the optimal management of the global WEL system. If measures are not taken to extend accountability for the indirect pressures imposed across the global WEL system, the resource burden of consumption will be greatly mismanaged.

1. Introduction

The supply chains of goods and services rely on systems of production that are spatially disaggregated and organisationally complex (Bode and 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 (Cabernard et al., 2019). This can implicate a sector's immediate production and upstream suppliers in its overall resource footprint. For example, a clothing retailer will use energy directly to operate its stores (tier one), but will also rely indirectly on energy use in factories to manufacture its clothes (tier two), and further upstream its supply chain, on water, land and energy in cotton farming to supply those manufacturers (tier three+). Understanding how country and sector resource dependencies are distributed across their supply network is critical to pinpoint where interventions to reduce their impact should be targeted (Wiedmann and Lenzen, 2018).

The complex and globalised nature of supply chains has rendered country and sector resource footprints borderless and cross-sectoral in scope. As a result, the ability of governments or businesses to manage their sustainability through direct operations or via immediate suppliers has become increasingly challenging (Hertwich and Wood, 2018). However, locating where environmental impacts occur deeper within country and sector supply chains has only partially been explored due to the scale at which multi-dimensional resource footprinting analysis is undertaken and unpacked. Several factors have prevented a more comprehensive understanding of country and sector resource footprints. First, as guided by scholarship on the water–energy–food nexus (Galaitsi et al., 2018), multi-dimensional footprinting analysis has assigned primary importance to coupled pathways of resource use, overlooking the totality of country and sector resource dependencies (Taherzadeh et al., 2018). Second, resource footprinting analysis tends to be presented in an aggregate manner for cross-comparison purposes, but this inadvertently hides the focal supply tier(s) where country and sector pressures on the WEL system arise (Wiedmann and Lenzen, 2018). Third, studies levelled at analysis of country and sector supply chain sustainability are often truncated by their reliance on physical inter-industry and inter-country trade data which only partially trace supply networks (Malik et al., 2021). Consequently, a global and economy-wide supply chain perspective of country and

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sector resource footprints is needed to understand opportunities and risks for their sustainable management (Vivanco et al., 2018b).

A supply chain perspective of country and sector resource footprints is needed on several fronts. First, variations between the profile of resource use between sectors, countries and environmental systems demand different management approaches to ensure their sustainability. Fig. 1 illustrates two cases where 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 upstream and downstream supply chains (Sector B). As such, mapping the profiles of resource use across supply chain networks reveals how water, energy and land resources can be managed in an integrated manner. Second, by identifying which supply tier(s) contribute most towards country and sector resource footprints, supply chain actors (e.g. producers or manufacturers) pertinent to their sustainability can be identified and prioritised (Afionis et al., 2017). Third, knowledge of the supply chain scope of country and sector resource footprints can help to inform the appropriate focus of future sustainability policies and monitoring measures which are often defined *a priori* without a systematic understanding of their coverage (Taherzadeh et al., 2018).

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 chains of consumption activities (e.g. linked to global, national or sectoral demand) to assess their production requirements and associated environmental impacts upstream and downstream supply networks (Kitzes, 2013). PLD and its tier-based perspective of country and sector resource footprints has two main advantages over prevailing scope-based supply chain sustainability accounting. First, whilst both accounting approaches aim to capture both direct and indirect environmental impacts embodied in supply chains, PLD unpacks indirect impacts by each production layer, offering a more detailed impact profile of countries and sectors. Second, PLD can be applied to any environmental impact area due to its inter-sectoral nature, but scope-based assessment focuses singularly on greenhouse gas emissions embodied in supply chains (Hertwich and Wood, 2018).

To date, the application of PLD has mostly been levelled at assessment of carbon emissions, at a sectoral (Rodríguez-Alloza et al., 2015; Lenzen et al., 2018), national (Schmidt et al., 2019), and macro-regional scale (Kucukvar and Samadi, 2015; Giljum et al., 2016). 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' emissions at different stages of their supply chains (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. Giljum et al. (2016) offer the most substantial PLD of sector material footprints (covering minerals, biomass, fossil fuels and metal ores), focusing on EU-28 consumption, and found a noticeable shift in sectoral resource pressures further upstream their supply networks between 1995 and 2011, underlining the need for such a supply chain perspective of country and sector resource footprints. Other studies focus on specific countries and their sub-regions. Guan et al. (2019) performs a detailed PLD of water, energy and land use pathways for China and finds that tier three producers account for around 70% of embodied energy use and indirect demand (tiers two and above) accounts for around half of total embodied water use and just over 40% of total land use. Whilst Veiga et al. (2018) constructs a supply chain profile of energy use and carbon emissions driven by sugar production in São Paulo state, highlighting their indirect nature (>40% for energy use and 97% for carbon emissions). For energy-related footprinting, PLD has been used more widely, but its applications have been limited to case studies of specific sectors. Heihsel et al. (2019) evaluates the embodied greenhouse gas emissions related to desalination in Australia and finds a high proportion of these impacts occur upstream its supply network, from desalination inputs and emitting industries. At similar scope, Malik et al. (2016) conduct an economy-wide evaluation of the greenhouse gas emissions and energy use associated with greater use of biofuels in the Green Triangle region of South Australia and conclude that truncating environmental accounting at tier 3 would ignore 31% of energy and 27% of greenhouse gas impacts of the cellulose-refining industry. The importance of upstream suppliers to sectoral greenhouse gas emissions is also highlighted in a study of a drink's supplier in Australia by Lenzen (2008b). For land, no cross-country applications of PLD were found at the time of writing. Viewed collectively, PLD studies have underlined the increasing importance of full supply chain accounting to capture fully the impact of countries and sectors. However, they also offer a fragmented picture of how water, energy and land use *and* risk is distributed across national and sectoral supply networks. This study attempts to bridge gaps in supply chain resource footprinting, improving upon the country, sector and environmental coverage of previous studies. The purpose of this study is two-fold. First, to understand the profile of country and sector resource footprints from a multi-dimensional resource perspective. Second, to examine the implications of boundary setting on coverage of resource pressures driven by countries and sectors. This analysis also provides ample data to interrogate the suitability of single-tier management approaches, such as those prescribed by the resource nexus concept.

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 country and sector supply chains;
2. priorities for integrated management of water, energy and land use across different sectors; and
3. the effects of truncating resource assessment to tier one and tier two of country and sector supply chains.

Section 2 outlines how resource use and resource risk across the global WEL system can be evaluated via decomposition of national and sectoral supply networks. The findings of this analysis, reported in Sections 3.1 and 3.2, convey the importance of different supply chain tiers for integrated management of country and sector pressures across the global WEL system, respectively. Section 4 comments on the significance and limitations of these findings and their implications for future research on the global WEL system. Section 5 summarises the study's main recommendations for natural resource management.

The findings of this study invite a refocusing of natural resource management around upstream suppliers and indirect resource consumption, alongside a 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 tier three+ impacts of sectors on greenhouse gas emissions (Redevco, 2019; Farsan et al., 2018; Richards, 2018; Kanemoto et al., 2020; Wiedmann et al., 2020), this assessment highlights the need to extend this agenda to water, energy and land resources.

2. Methods and data

Several methods have emerged to assess the resource use embodied in country, sector and business supply chains. These can broadly be categorised into physical flow or financial flow approaches, although the use of hybrid physical–financial approaches are becoming increasingly common in order to combine the strengths of each (see Bruckner et al. (2019), Croft et al. (2018), Hong et al. (2021)). Physical flow approaches, such as Life-Cycle Analysis (LCA) or Material Flow Accounting (MFA) rely on physical production, consumption and trade accounts to evaluate the required production inputs, resource use and pollution driven by a country, sector or business. Such data

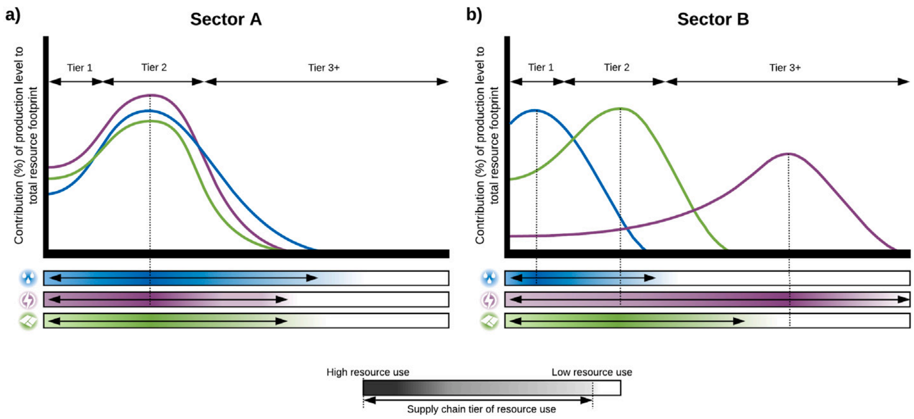


Fig. 1. Profiles of resource use across supply networks.
Schematic exemplifying different profiles of water, energy and land footprints in sector supply networks. Sector A illustrates a sector where water, energy and land use are concentrated at the same stage (tier two) of its supply network, implying 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.

often distinguish individual products and their resource intensities (Hubacek and Feng, 2016). Despite this high sectoral resolution, physical flow data are insufficient to map all supply chain relationships between countries and sectors and their use often results in a truncated scope of resource footprinting (Malik et al., 2021). In contrast, financial flow approaches, such as Input-Output Analysis (IOA), tends to offer a lower sectoral resolution than physical flow accounts, but enable full traceability of country and sector supply chains owing to the detailed inter-industry relationships revealed by financial flow data (Wiedmann and Lenzen, 2018). Within the context of this study, the superior supply chain coverage of financial flow data and its economy-wide coverage, led to the selection of IOA and underlying data. IOA attempts to understand the structure of the economy in terms of the interdependencies between sectors and households (Suh, 2009). The process of using IOA to assess the resource footprint of country and sector consumption is made possible via a straightforward matrix inversion and vector multiplication calculation using available data on inter-industry financial transactions and their associated environmental resource requirements (Kanemoto et al., 2012). In contrast to MFA, IOA uses monetary transactions between sectors of the economy, which are more widely available than their physical equivalents at such scale, to estimate these interdependencies. Although financial networks provide only a proxy for physical dependencies between sectors, the superior coverage of economic accounts enables IOA to assess more fully the resource use embodied in national and sectoral consumption when compared with MFA (Hubacek and Feng, 2016). IOA when employed within a multi-regional, trade-based context, is referred to as Multi-Regional Input Output Analysis (MRIOA) and relies on MRIO databases which integrate national IO tables. Within this study, an MRIO database, described in Section 2.2, is used in order to comprehensively profile resource use embodied in country and sector supply networks.

2.1. Production layer decomposition

This section outlines how PLD is applied to the assessment of country and sector resource pressures across the global WEL system. Quantitatively, PLD of a country's or sector's resource footprint, F, is achieved by expressing the Leontief demand-pull equation $F = f\mathbf{L}y$, well documented elsewhere (Miller and 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:

$$F = F_1 + F_2 + F_3 + \cdots = fy\mathbf{I} + \mathbf{A}fy + \mathbf{AA}fy + \cdots = [\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots]fy \quad (1)$$

where F refers to a resource intensity vector, y refers to a given level of final demand, and $\mathbf{A}$ refers to the technical coefficients matrix describing sectoral interdependencies.

Since all values in the $\mathbf{A}$ matrix are below 1, the power series (1) converges to zero as the number of production levels n increases. This stepwise calculation can be used to evaluate the overall water, energy and land footprint of countries and sectors at different stages of their supply network. Within this assessment, 11 production levels are examined which capture on average >95% of the overall water, energy and land footprint of 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, following the methodology described in Taherzadeh et al. (2020). 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:

$$\underset{0,1}{f_c} = [RI_c \geq \frac{RI^{max}.i - RI^{max}}{3}].[RI_c \leq \frac{RI^{max}.i}{3}] \quad (2)$$

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 RI is the raw index value data for a country, c.

2.2. Data sources

This section details the underlying data used to model country and sector pressures across the water–energy–land system. WaterStat (2019) provide a measure of agricultural and industrial water use data for countries and sectors. This database, developed by Hoekstra and Wiedmann (2014), is constructed from two underlying datasets. Agricultural water use is sourced from the UN Food and Agriculture Organisation (FAO) which reports member countries' agricultural water use via a yearly survey administered by their national authorities (Mateo-Sagasta and Salian, 2012). Industrial water use is sourced from FAO (2020) and Eurostat (2020) and is described in Hoekstra and Mekonnen (2011). This analysis aggregates blue water use (from groundwater and aquifers) and green water use (precipitation and evapo-transpiration) to evaluate the total consumption-based water footprint of countries. Within this analysis, projected national blue water scarcity under a near-term (2020) business-as-usual climate scenario, sourced from WRI (2015), is used to infer country-level water risk.

Energy use data were sourced from the International Energy Agency which covers twelve energy sources: natural gas, coal, petroleum,

Table 1
Resource use and risk data sources.

Resource	Measure	Units	Resolution	Year	Source
Water footprint	Agricultural and industrial blue water use (from groundwater and aquifers) and green water use (precipitation and evapo-transpiration)	m^3	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	m^3	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	Zhang et al. (2016) Yale University (2019)

nuclear, hydroelectric, geothermal, wind, solar, tide, wave, biomass, and waste, collected and reported by national authorities (IEA, 2019). Energy risk data were sourced from the World Energy Council (2018) Energy Index. This index measures national energy security based on countries' prudent management of domestic and imported energy, energy infrastructure reliability, and the preparedness of energy providers to meet current and future energy demand.

Land use data were sourced from the UN FAO (2019), as is common in other land footprinting studies (see Taherzadeh and Caro, 2019; Bruckner et al., 2019; Hong et al., 2021). This database captures the cultivated area for 172 crops based on data reported by member countries' national authorities. Land risk data capture the productivity *and* sustainability of agricultural land use, based on the Sustainable Nitrogen Management Index (SNMI), developed by Zhang and Davidson (2016), using data from FAO (2019) and compiled by Yale University (2019) in 2010. The SNMI measures (i) the fraction of nitrogen input harvested as product (i.e. nitrogen use efficiency, as defined in Zhang et al. (2015), and (ii) land use efficiency (i.e. harvested nitrogen).

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. Limitations of the risk-based indicators applied within this study can be found in Taherzadeh et al. (2020).

For the purpose of cross-sectoral comparison at a global scale, an aggregated version of the Eora (2019) database which distinguishes 24 major sectors[1] 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 4. All analysis employs country and sector economic accounts in 2015.

Section 3 presents the supply chain decomposition of country and sector water, energy and land footprints and risk in 2015. After summarising the global picture, supply chain profiles of national resource footprints are presented in Section 3.1. Sector-level differences are then presented in Section 3.2. In both sections, the implications of truncating resource footprinting and risk assessment are discussed and priorities for supply chain sustainability measurement outlined. All data relating to analysis within this study can be found in the supplementary data. Section 4 discusses the study's findings within the context of current supply chain research and management and also comments on its limitations 4.1. The wider management implications and future research priorities are discussed in Section 5

[1] Excluding 'Others' and 'Re-export and Re-import' from EORA26 due to their limited relevance within the context of this study.

Table 2
Contribution of tier one-three+ resource use to global resource footprints.

	Global water footprint (% Total)	Global energy footprint (% Total)	Global land footprint (% Total)
Tier one	1.32 Tm^3 (13.9%)	54.9 EJ (11.7%)	0.493 Gha (15.9%)
Tier two	3.36 Tm^3 (35.4%)	131 EJ (27.8%)	1.07 Gha (34.6%)
Tier three+	4.80 Tm^3 (50.6%)	285 EJ (60.5%)	1.53 Gha (49.5%)

Table 3
Contribution of tier one-three+ resource use to global resource risk.

	Global high risk water footprint (% Total)	Global high risk energy footprint (% Total)	Global high risk land footprint (% Total)
Tier one	0.171 Tm^3 (1.83%)	5.89 EJ (32.3%)	35 Mha (3.25%)
Tier two	1.01 Tm^3 (10.8%)	5.06 EJ (27.8%)	302 Mha (28%)
Tier three+	8.18 Tm^3 (87.4%)	7.26 EJ (39.9%)	740 Mha (68.7%)

3. Results

The importance of tier two and tier three production is underlined by their contribution to pressures of global consumption across the global 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 countries and consumption sectors. These differences are discussed by referring to the 'supply tier' of sectors. Tier one refers to a country's or sector's first and direct production layer, comprising an aggregate of businesses' operational activities and their production and resource demands at an industry-level (for sectors) and economy-wide scale (for countries). Tier two refers to the production and resource dependencies embodied in immediate suppliers of these focal businesses and is aggregated in the same way. Tier three refers to the suppliers of these immediate suppliers, and so on. 'tier three+' refers to an aggregate of all production layers and resource impacts beyond tier two.

3.1. 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 and manage the total 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 global 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.

Fig. 2 illustrates the primacy of different production levels and supply chain tiers to national water, energy and land footprints across the 189 countries analysed. Within the majority of countries tier three+ suppliers contribute more greatly than tier one or tier two 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 Fig. 2. The importance of tier three+ 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%). Moreover, as shown in Fig. 2, tier three+ 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 in Fig. 2. For example, tier one 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 tier two (39%) and tier three+ (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 water, energy *and* land footprints are imposed in tier one of their supply network, and between two-thirds and three-quarters is concentrated in tier three+.

Fig. 3 presents a series of box plots capturing variation in the contribution of tier one, tier two and tier three+ production levels to national water, energy and land footprints and high risk resource use in 189 countries.

This cross-cutting analysis reveals several qualities about the supply chain scope of national pressures across the global WEL system. First, on average, tier one production accounts for between 5% and 20% of the overall resource demand of countries across the global WEL system. Second, tier three+ production (upstream suppliers) contributes on average more than both tier two (direct suppliers) and tier one within this context. Even when aggregated, tier one and tier two suppliers account for between 40%–50% of total national water, energy and land footprints. Third, the contribution of tier two 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 tier three+) than overall resource demand across these systems (Fig. 3).

Although highly significant to national water, energy and land footprints, tier three+ resource use accounts for a total of nine levels (3–11) of their supply network so implicates a large number of suppliers. Disaggregating tier three+ production helps to identify the most significant production level contributing to national pressures across the global WEL system, when tier three+ production levels are treated as nine discrete production levels. On average, production layer two (i.e. tier two) 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 global WEL system. Tier one production is the greatest source of high risk energy use. However, tier two suppliers account for the greatest source of high risk water and land use when viewed from an individual production-layer persepctive.

3.2. 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.

Fig. 4 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 (2019) 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 in tier one of agricultural supply chains (i.e. on farms) (Fig. 4-1). However, only 21% of the energy footprint and 36% of the high risk energy footprint of the *Agriculture* sector is due to its indirect energy use. As Fig. 4-1 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 tier two of its supply network (Fig. 4-4). Strong alignment between the supply chain profile of water, energy and land use is also seen in several other sectors, including *Textiles and Apparel* (Fig. 4-5), *Wood and Paper* (Fig. 4-6), and *Construction* (Fig. 4-14). However, for the majority of sectors, a mismatch between the concentration of resource use and resource risks in supply networks is observed (see Fig. 4). For example, tier one resource use accounts for the large contribution to energy footprints in *Electricity, Gas and Water* (Fig. 4-13), *Transport* (Fig. 4-19), *Mining and Quarrying* (Fig. 4-3), and *Petroleum and Mineral products* (Fig. 4-7) sectors but an insignificant proportion of water and land footprints.

In contrast, resource use in some sectors is highly diffuse across their supply network — see *Metal Products* (Fig. 4-8), *Electrical and Machinery* (Fig. 4-9), *Transport Equipment* (Fig. 4-10), and *Other Manufacturing* sectors (Fig. 4-11). 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.

When considered within the context of sectoral supply chain scopes, the major contribution of tier two and tier three+ pressures on water, energy and land resources is seen more clearly. Fig. 5 presents an aggregated view of resource use and resource risk imposed by sectors across the global WEL system in relation to tier one, tier two and tier three+ suppliers. The contribution of tier one production to water, energy and land use embodied in supply chains varies between sector and resource systems.

On average, tier one 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 tier one 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, tier one production accounts for a higher proportion of sectoral high risk water use (median = 7.9%, mean = 17.4%) than high risk land use. Tier two

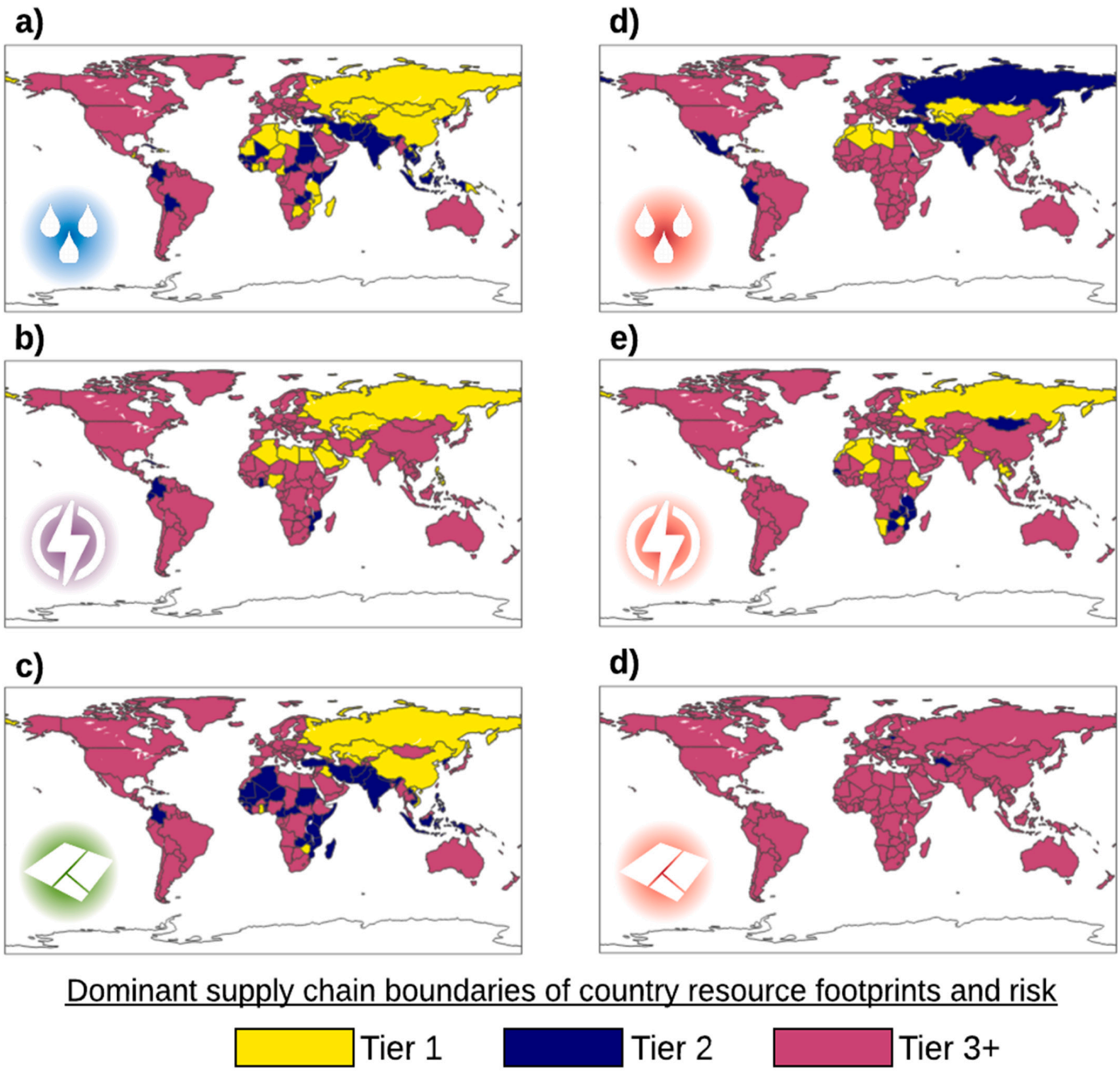


Fig. 2. Contribution of tier one–three suppliers to national water, energy and land risks.
Choropleth map illustrating the supply chain tier (1–3) of primary importance to national (a) water, (b) energy and (c) land footprints and risks (d-f). Country colouration is based on which supply chain tier (1–3) accounts for the largest share (i.e. more than 33.3%) of its total or high risk resource footprint. A full production layer decomposition of country resource footprints can be found in the supplementary data.

production accounts for a more significant source of sectoral energy footprints in 18 of the 24 sectors analysed.

More broadly, tier two production is found to be a greater source of resource pressures and risk across WEL resources than tier one production in 16 of the 24 sectors modelled. However, tier three+ production is found to account for a greater proportion of sectoral resource pressures than tier two production in most sectors, as illustrated in Fig. 4.

Tier three+ 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 high risk energy use (median = 45.9%, mean = 42.2%). Consequently, truncating resource assessment across the global WEL system to only tier one and tier two overlooks a potentially large share of sectoral water, energy and land resource pressures.

4. Discussion

Globalisation, outsourcing and subcontracting of production processes have led to an expansion in the supply networks of countries and sectors (Maluck and Donner, 2015). As a result, dependence on remote suppliers (i.e. suppliers of suppliers) within global production and consumption systems has increased (Blackhurst et al., 2011). Despite their growing significance, businesses often have limited understanding

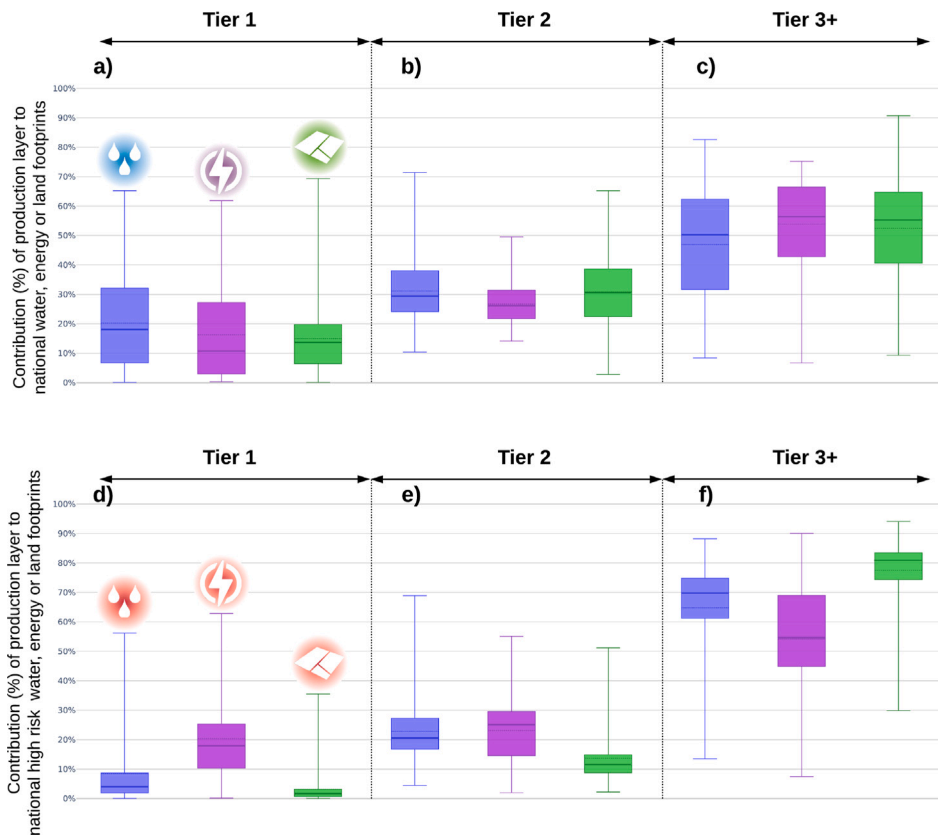


Fig. 3. Distribution of tier one-3+ production embodied in national WEL pressures.
Box plot illustrating the contribution (%) of tier one (a,d), tier two (b,e) and tier three+ (e,f) suppliers to national water (blue), energy (purple) and land (green) footprints (top) and national high risk water, energy and land use (bottom). Box plots represents inter-quartile range; mean values = dashed lines; median values = solid lines.

of the regulatory, environmental, and social context of their upstream suppliers, when compared with their own operations and those of their immediate suppliers (O'Rourke, 2014). Limited knowledge of their full supply chain 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 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); and more recently from Covid-19 induced supply chain disruptions (Vidya and Prabheesh, 2020).

Identifying opportunities for integrated management of country and sector pressures across the global 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 tier one suppliers, immediate suppliers (tier two), and upstream suppliers (tier three+) to national and sectoral resource pressures across the global WEL system.

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 (tier three+) 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 exhibit large variation within and between sectors. These findings reveal both challenges and opportunities to the integrated and sustainable management of pressures across the global 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 resource nexus concept. Although water and land use appear closely coupled in global supply networks (see Fig. 4), 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.

4.1. Limitations and research priorities

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 within 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

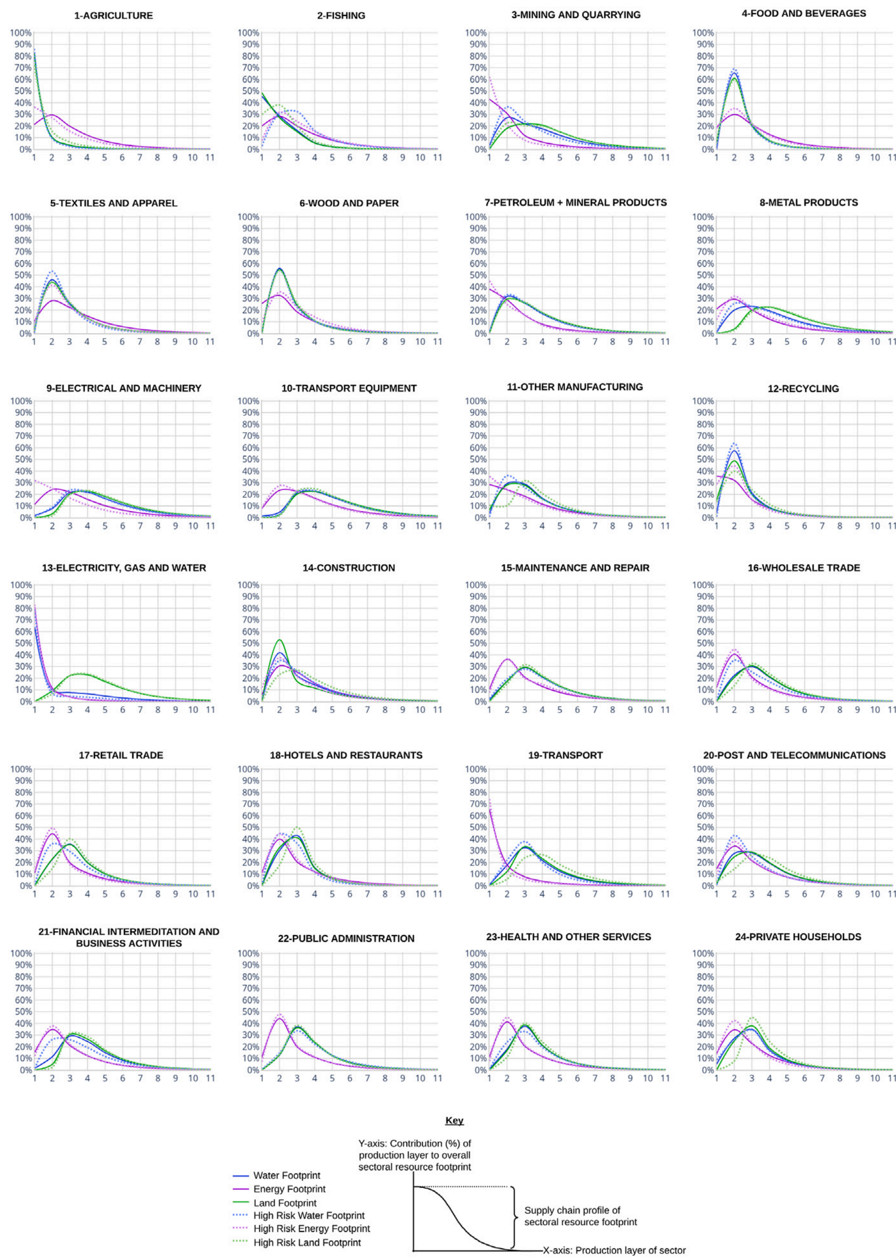
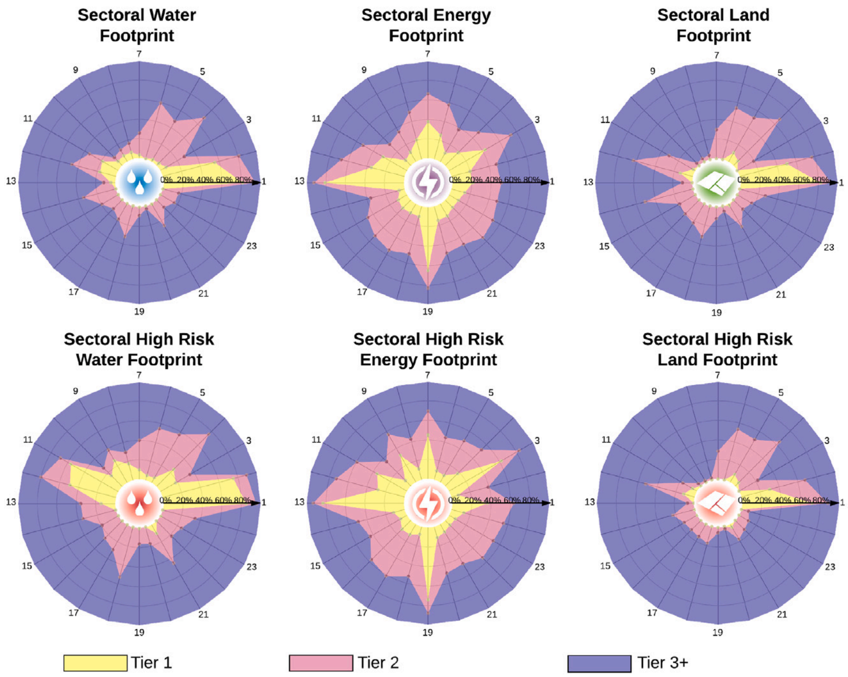


Fig. 4. Supply network decomposition of WEL pressures in major global sectors.
Series of plots illustrating the contribution (%) of different production layers (x-axis) to the water, energy and land footprints (y-axis) of 24 global sectors.

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 incomplete data. Although resource risk data exists at a higher spatial resolution for water (Xu et al., 2019; Masud et al., 2019; Pfister et al., 2020, 2011b; Quinteiro et al., 2018; Hoekstra et al., 2012; Lutter et al., 2016), energy (BEIS, 2018; Faturay et al., 2020), and land resource use (Godar et al., 2015; Godar and Gardner, 2019; Croft et al., 2018; Chaudhary et al., 2016; Pfister et al., 2011a), these cannot meaningful be linked to economic accounts due to the limited sub-national detail of MRIO tables (Taherzadeh et al., 2020).

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 indeterminacy 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, indeterminacy ‘exists in the open-ended question of whether knowledge is adapted to fit the mismatched realities of application situations.’



No	Sector
1	Agriculture
2	Fishing
3	Mining and quarrying
4	Food and beverages
5	Textiles and apparel
6	Wood and paper
7	Petroleum and mineral products
8	Metal products
9	Electrical and machinery
10	Transport equipment
11	Other manufacturing
12	Recycling
13	Electricity, gas and water
14	Construction
15	Maintenance and repair
16	Wholesale trade
17	Retail trade
18	Hotels and restaurants
19	Transport
20	Post and telecommunications
21	Financial and business activities
22	Public administration
23	Health and other services
24	Private households

Fig. 5. Contribution of tier one-3+ suppliers to sectoral resource footprints.
Series of polar charts illustrating the contribution of tier one, tier two and tier three+ production to sectoral (a) water, (b) energy and (c) land footprints and high risk (d) water, (e) energy (f) and land footprints (bottom). Numbers on radial axes correspond to sectors in the key. Default colour scheme adapted to improve readability.

This is pertinent to MRIOA as well as the burgeoning application of the nexus concept to understand and manage pressures across the global WEL system. Nevertheless, the current inadequacies of physical commodity accounts illustrate why this study necessitates the use of MRIOA (or a hybrid physical-financial appgroach).

Another source of indeterminacy relating to MRIOA pertains to the normative nature of consumption-based accounting which, unless modified (Andrew and 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 (geographically and administratively) of tier three+ producers and decisions from downstream consumers (Afionis et al., 2017). 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 and risk sharing within the global 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 3–11 of country and sector supply into tier three+ conflates a large proportion of economic and environmental activity. Where appropriate, the significance of specific production layers in tier three+ is made explicit (see Fig. 4, Section 3.1).

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 coefficients 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 FABIO (Bruckner et al., 2019) 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 commodities and may 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 all country sectors would involve 27,216 (24 sectors x 189 countries x 6 resource use indicators) observations, distracting from the overall focus of this 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.

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 and Murray, 2010; Wood and 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. (2018b) 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.

Another promising avenue for multi-dimensional resource footprinting is the use of indicators which capture the interactions and hot-spots of resource use embodied in country and sector supply chains. In terms of indicator development, composite metrics, network indicators and cluster analysis stand to offer unique and policy relevant perspectives on country and sector resource pressures across the global WEL system. Composite metrics which capture the level of heterogeneity amongst water, energy and land use pathways, such as the 'nexus strength' indicator proposed by Vivanco et al. (2018a) which measures correlation between CBA and PBA perspectives of WEL footprints, can help to identify production and consumption contexts where these systems can be managed in an integrated manner and where they are best managed independently. Important suppliers, sectoral inter-dependencies, and resource use paths can also be identified by studying the influence and sensitivity of economic agents (i.e. countries or sectors) across a weighted input–output network of resource use. Network-related indicators, including *inter alia* weighted in-degree and out-degree (Distefano et al., 2018), betweenness centrality (Hanaka et al., 2017), and the page rank algorithm (Deguchi et al., 2014) offer different perspectives on country and sector authority across resource use networks. Weighted in-degree and out-degree identify major sources of resource demand and supply within resource use networks, respectively. Betweenness centrality captures the proximity of countries and sectors to a given source of production and resource use; this measure can be interpreted as an indicator of vulnerability or exposure to upstream or downstream resource use decisions. Similar to in-degree and out-degree, page rank can be used to measure the authority of countries and sectors based on the volume and weight of their in-going (demand-side) and out-going (supply-side) resource use flows. Lastly, cluster analysis of resource use networks can help to identify important groups of highly interconnected sectors where resource management interventions could be targeted. Such management clusters have been shown to exist within the context of global networks for greenhouse gas emissions (Kagawa et al., 2013; Hanaka et al., 2017, 2021; Li et al., 2017; Kanemoto et al., 2019) and water use (Konar et al., 2011; Tian et al., 2018; D'Odorico et al., 2012).

The practical requirements for implementing integrated environmental management have received little attention (Green et al., 2016). It may be the case that appraisal of policy measures within a nexus-context can be undertaken within the existing governance structures that surround natural resource management. However, management of the water–energy–land system could also imply a fundamentally different mode of decision making and institutional responsibility in the area of resource management (Hoff, 2011). Within this context, significant knowledge gaps exist in relation to effective incentive systems, regulatory requirements, and the role of cross-cutting administrative units in promoting synchronised management (Rees, 2013). Transition to such a system of integrated management is unlikely to be straightforward. Water, energy, and land management regimes operate at different and overlapping spatial scales presenting unique challenges to policy coordination (Leck et al., 2015). Time and resource constraints of individual policy administration entities, imperfect knowledge surrounding interactions of policy outcomes, and vested interests in different areas of decision-making, may all impede such coordination. Equally, (re)configurations to facilitate effective ownership of the nexus agenda might have unintended consequences; cross-departmental integration of environmental decision making pose the risk of diluting the responsibility and accountability of individual departments (Wichelns, 2017). Consequently, there is a critical need to identify the barriers to governing the water–energy–land system and how they can be overcome (Lele et al., 2013). The study of environmental policy integration, nationally (Persson et al., 2016) and globally (Nilsson et al., 2016; Hagemann and Kirschke, 2017), alongside the growing number of contexts in which nexus-based governance is being evaluated and operationalised (e.g. in China (Biba, 2016), Brazil (Mercure et al., 2019), and the UK (Cairns and Krzywoszynska, 2016), and from legal (Larcom and van Gevelt, 2017) and cross-sectoral perspectives (Boas et al., 2016)), provide a reference for such evaluation. Although highly important, the scope of this study does not lend itself to the close examination of governance principles for integrated management of the WEL system. Whilst sophisticated quantitative analysis can help to identify focal points (i.e. sub-systems) of the WEL system which exert a major influence on the demand for natural resources, an analysis of the political economy of global value chains is necessary to unpack fully the challenge of achieving sustainable systems of production and consumption (Heron et al., 2018). The absence of this perspective is symptomatic of wider scholarship on the WEL system which has been dominated by quantitative lines of enquiry with few practical recommendations for its governance (Stirling, 2015).

5. Conclusion

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 are distributed throughout globalised systems of production, consumption and trade. This study improves upon previous scholarship levelled at supply chain analysis of country and sector resource footprints. First, it offers a supply chain perspective of resource use pathways for a wider range of countries (189 in total) which have previously been analysed at an aggregated level (e.g. the EU-28 or OECD), or overlooked entirely. This offers a new evidence base to inform national supply chain sustainability reporting guidelines based on a global, economy-wide analysis of their boundaries. Second, the multi-sectoral scope of this study helps distinguish the different resource use profiles and management priorities of different sectors which were otherwise unknown due to the partial and aggregated scope of resource-based PLD. Lastly, the multi-dimensional scope of this analysis, covering pressures and risks across the global WEL system, provides an integrated picture of the opportunities and risks concerning their management which are unclear from observations drawn from single impact PLD studies. The heterogeneity of resource use pathways, by sector, country and resource system, highlighted within this study underlines the importance of PLD at these scales in order to inform integrated environmental management. In addition to its empirical contribution, this study's findings invite greater reflection on the importance of coupled resource use pathways (i.e. the water–energy–land nexus) as a focus of multi-dimensional resource footprinting and management, showing that singular and less complex resource use pathways might contribute more significantly towards country and sector resource footprints. To this end, a whole supply chain perspective to integrated environmental management might offer a more practical and comprehensive frame for managing country and sector pressures across multiple resource systems.

Despite the complexity of water, energy and land use profiles in global supply networks and their governance, this assessment highlights several avenues for more effective assessment and management of country and sector pressures across the WEL system. First, extending the coverage of resource footprinting to tier three+ 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 tier two suppliers (i.e. immediate suppliers) (Richards, 2018). Accordingly, changes to such guidelines to encourage more comprehensive coverage of tier three+ 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 interdependent 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. Critically, resource management must recognise and accommodate the different ways in which sectors use natural resources in their supply chain. If measures are not taken to this end, the resource burden of consumption activities will be greatly mismanaged.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128701.

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