Tracing Pathways of Resource Use in the World Economy

An Analysis of National and Sectoral Influence across the Global Water-Energy-Land System

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I would like to dedicate this thesis to my Mother,
for her constant support, encouragement, and above all, love.

Declaration

I hereby declare that this dissertation is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University of similar institution except as declared in the Preface and specified in the text. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. I confirm this dissertation contains fewer than 80,000 words, in line with the regulations of the University of Cambridge Department of Geography Degree Committee.

Oliver Ahrash Taherzadeh
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Abstract

A research and policy agenda has emerged in recent years to understand the interconnected risks natural resource systems face and their exploitation drives. The so-called Water-Energy-Food (WEF) nexus has served as a focal point for the conceptual, theoretical and empirical development of this agenda. However, boundaries for WEF nexus assessment are usually established without a foundational understanding of major interactions and risks across the water-energy-land (WEL) system. Consequently, priorities drawn from nexus studies might simply be an artefact of the partial scope of nexus assessment rather than a reflection of major risks to the WEL system and the activities which it supports. This thesis demonstrates how macro-economic methods of resource accounting can be used to broaden nexus assessment, sectorally and spatially, to identify and compare different sources of water, energy and land use, in individual countries and globally.

A study of water and land use embodied in international soybean trade (Chapter 3) reveals that while single commodities can be analysed in this way, data and time constraints involved in using Material Flow Analysis (MFA) data make global assessment of water, energy and land use pathways across different production and consumption systems challenging. However, Multi-Regional Input-Output Analysis (MRIOA) is found to offer a practical approach to this end. By combining economic and environmental accounts from the Eora MRIO database, resource risk indices, and techniques for production source decomposition, this thesis examines the water, energy and land footprints of 189 countries. Chapter 4 evaluates the scale of national water, energy and land use embodied in domestic production and international trade; Chapter 5 compares the contribution of food and non-food related sectors within this context; and, Chapter 6 reveals how these impacts are distributed across supply networks.

Linking national consumption to resource origins reveals that countries are often highly exposed to over-exploited, insecure, and degraded water, energy, and land resources. These risks are found to originate from multiple sectors, including food, textiles and construction, and are primarily indirect, stemming from international trade and production up-stream national supply networks. These findings highlight the partiality of studying the WEL system within a single sector, across a limited supply chain scope, and at a sub-global scale. Policy interventions within this context need to reflect how resource pressures are transmitted through consumption and production systems between local, national, and global scales. However, further research is also needed to expose the links between inequality, ideology, overconsumption and environmental exploitation which drive decisions in relation to water, energy and land resources.

Preface

Dr Mike Bithell and Professor Keith Richards (Department of Geography, University of Cambridge) supervised this dissertation. Dr Dario Caro (Aarhus University) conceived of the case study in Chapter 3 and was responsible for the analysis and figures in Section 3.3.1, and drafting of Sections 3.2.1, 3.2.2, 3.2.3, 3.2.4, 3.2.5 and 3.3.1. I was responsible for supplying the underlying production, consumption and trade data used in the study, analysis and figures in Section 3.3.2, writing of Sections 3.1, 3.2, 3.5, 3.3.2, 3.4, 3.5, and editing the Chapter and related journal publication. The development of research ideas, the empirical design, collection and analysis of data, and the writing and editing for all other chapters contained within this thesis represent my own work. Data and analysis relating to Chapters 3-6 is available from Taherzadeh (2020).

Peer-reviewed publications

- **Taherzadeh**, O., Bithell, M. and Richards, K. 2018. When defining the boundaries of nexus analysis, let the data speak. *Resources, Conservation and Recycling* (137): 314-315. doi: https://doi.org/10.1016/j.resconrec.2018.06.012 [**Chapter 1**]

- **Taherzadeh**, O. and Caro, D. (2019). Drivers of water and land use embodied in international soybean trade. *Journal of Cleaner Production* (223):83-93. doi: https://doi.org/10.1016/j.jclepro.2019.03.068 [**Chapter 3**]

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Conference proceedings and presentations

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Nomenclature

Acronyms / Abbreviations

IOA	Input-Output Analysis
LCA	Life Cycle Analysis
MFA	Material Flow Analysis
MRIOA	Multi-Regional Input-Output Analysis
PLD	Production Layer Decomposition
PTA	Physical Trade Analysis
VLT	Virtual Land Trade
VWT	Virtual Water Trade
WEF	Water-Energy-Food
WEL	Water-Energy-Land

Chapter 1

Introduction

> When we try to pick out anything by itself we find that it is bound fast by a thousand invisible cords that cannot be broken, to everything in the universe
>
> *John Muir (1869)*

1.1 Background

A minimum condition of sustainable development is that demand for goods and services is met without harming the biophysical processes on which they depend (Hickel & Kallis, 2019). However, both in individual countries, and globally, such a condition has not been met (Erb et al., 2012; Krausmann et al., 2018; Steffen et al., 2015). Instead, development has begun to overstep the limited regenerative and assimilative capacities of our biosphere (O'Neill et al., 2018). This is observable for three critical resources which underpin development: water (Gleick & Heberger, 2014), energy (Seppelt et al., 2014), and land (IPBES, 2018). The impact of human activity across the Water-Energy-Land (WEL) system is unprecedented within history (Steffen et al., 2015). Major water basins have been over-exploited (Wang & Zimmerman, 2016), some at fifty times their replenishment rate (Tuninetti et al., 2019), resulting in an estimated four billion people affected by severe water scarcity; global energy demand, primarily for fossil fuel resources, has brought humanity dangerously close to tipping points in the climate system (IPCC, 2014); and, world-wide, over three-quarters of potentially productive land has been degraded (IPBES, 2018). The factors contributing towards this trilemma - economic development, population growth and technological change - are abundantly clear. However, the exact pathways of water, energy and land use have become increasingly complex to unpick, sort, and reconcile with meaningful policy interventions.

In recent decades, resource pressures have shifted from local to global production and consumption contexts (Giampietro, 2014). Consequently, local resource problems related to water stress (Allan, 2003; Dalin et al., 2017; Lenzen et al., 2013a; Vörösmarty et al., 2015), energy demand (Davis & Caldeira, 2010; Kander et al., 2015; Zhang et al., 2017) and land degradation (Bruckner et al., 2015; Chen & Han, 2015; Godar et al., 2015), are increasingly determined by consumptive decisions made beyond national borders. This can be observed in the rise of trade in agriculture and livestock products (MacDonald et al., 2015; Taherzadeh & Caro, 2019; Zanten et al., 2016), fossil fuels (Davis & Caldeira, 2010), manufactured goods (Zhang et al., 2017), and services (Victor & Rosenbluth, 2007). The overall resource burden of human activity has also grown dramatically.

During the 20th century, global population quadrupled and global economic output grew more than 20-fold (Maddison, 2001). This expansion saw the extraction of construction materials grow by a factor of 34, ores and minerals by a factor of 27, fossil fuels by a factor of 12, and biomass by a factor of 3.6 (Krausmann et al., 2009). Moreover, the number of competing demands for water, energy and land resources have grown, in step with the increasing diversity of goods and services consumed within society. New demands on natural resources, from the built environment, transport sector, and consumer goods, have accompanied the shift of societies from agrarian to industrial regimes (Krausmann et al., 2016). These many pathways of water, energy and land use have also become increasingly fragmented as production processes have been outsourced and subcontracted (Los et al., 2015).

Notwithstanding these characteristics of human influence on the WEL system, recent scholarship has restricted its analysis to competition between these resources for *food supply*. The trade-offs between water, energy and food supply were first recognised in 1983 with the Food-Energy Nexus Programme of the United Nations University (Kurian & Ardakanian, 2015). This programme acknowledged the need (i) to protect the dual entitlements of individuals to food and energy demand and (ii) to promote better management of energy-food interdependencies in the case of fertiliser and fuel production (Sachs & Silk, 1990). The dependencies between natural resources were brought into sharper focus during the so-called 'Green Revolution', which spanned the 1950s and 1960s and saw agricultural production in developing countries shift from from low- to high-input systems as a result of mechanisation and intensification of farming to accommodate new crop varieties (Stone, 2019). Within this context, energy availability was acknowledged as an increasing constraint on water use within food production (Hellegers et al., 2008; Scott et al., 2003; Scott & Shah, 2004; Siegfried et al., 2008). In developed countries, concern also grew over the threats of freshwater stress and water shortages posed to continued industrial development, arising from competition for water between food and energy production (Ballard et al., 1982; Devine et al., 1980; Hightower & Pierce, 2008). Meanwhile, the resource-related risks transmitted between both developed and developing countries, via international trade, received growing attention (Bringezu et al., 2003).

International trade in resource-intensive commodities highlighted a need to look beyond territorial resource use, in order to understand and measure the global, upstream environmental impacts embedded in consumption (Allan, 2011; Bruckner et al., 2015; Davis & Caldeira, 2010; Porkka et al., 2017). The 2008 global food crisis exemplified the tight embrace between these forces (Headey, 2011). These observations all highlighted the need for a systems approach to understand and manage linkages between social, economic, and environmental systems in an increasingly interconnected world (Hellegers et al., 2008). However, until recently, references to coupled or multiple resource interdependencies had only been made in a number of isolated cases and were only observed in a generalised form (Rees, 2013).

A perceptible shift in this research and policy agenda can be observed towards the end of the 2000s in an effort to deepen understanding of resource interlinkages and their consequences in different countries and sectors. In 2009 Sir John Beddington, the former Chief Scientific Advisor to the UK government, warned that mounting demand-side and supply-side pressures on water, energy, food and climate change created a 'perfect storm' of challenges for meeting future development objectives. Beddington (2009) asserts that the response of the scientific community to address these challenges "will not happen by default", indicating a need for a new, integrated approach to sustainability. As Allouche et al. (2015) note, around this time, management of this water-energy-food nexus (hereafter, the 'WEF nexus') began to eclipse sustainability as the ultimate goal of development. Several high-profile events focusing on WEF interlinkages helped to underline the critical need for 'a nexus approach' to understand and respond to the complex, and interconnected challenge of sustainable resource management (*cf* Bonn, 2011; WEF, 2008, 2014).

Although there exists no agreed definition of what constitutes a 'nexus approach', there is general agreement that it encompasses analysis of resource system relationships to promote management of individual resources in a manner that is consistent with the allocation and use of other resources (Kurian & Ardakanian, 2015). In this regard, management of 'the nexus' is said to address the weakness in prevailing single-sector approaches to research and decision-making in natural resource management which address one resource problem at the expense of another and fail to consider interdependencies (Leck et al., 2015). The aim of a nexus approach is not only to identify and avoid trade-offs in decision-making in natural resource governance, but also to highlight measures which meet multiple policy goals around resource use in a robust and sustainable manner (Bazilian et al., 2011). Such an approach is particularly relevant for understanding and managing policy interactions posed within the context of the recently adopted UN Sustainable Development Goals, which cover 17 goals and 169 targets for national and international development until 2030 (Boas et al., 2016; Nilsson et al., 2016; Ringler et al., 2013; Weitz et al., 2014).

Assessment of interlinkages across the WEF nexus have included *inter alia* assessment of the water and land impacts of using biofuel energy to reduce greenhouse gas emissions (Konadu et al., 2015a; Pfister et al., 2017; Scheidel & Sorman, 2012); the energy and land footprint of desalination plants designed to augment freshwater supply (Elimelech & Phillip, 2011; Shahzad et al., 2017); the energy burden of water supply and treatment (Blanc et al., 2016; Rothausen & Conway, 2011; Wang et al., 2012); and, the water requirement of energy supply (Holland et al., 2015; Huang et al., 2017; Janku, 2016; Qin et al., 2015). Within these contexts, such an integrated analysis has enabled exposure of otherwise unforeseen risks and opportunities arising from individual resource management (Bazilian et al., 2011). Despite its infancy, nexus scholarship has made novel theoretical and practical contributions to our understanding of natural resource interdependencies and their management. First, as Srivastava & Lyla (2014) note, the nexus agenda has highlighted a critical need to understand and manage resource linkages which have largely been forgotten or overlooked due to bureaucratic silos and single-sector management. Second, nexus thinking has helped to promote integrated resource management not only as a desirable goal, but as a new way in which sustainable development can be navigated within the context of multiple environmental tipping points (Gerten et al., 2013; Liu et al., 2015; Rees, 2013). Third, demand for nexus assessment has also promoted the development of a suite of analytical tools and methodological approaches for integrated resource analysis (Albrecht et al., 2018). However, boundaries for WEF nexus assessment are usually established without a foundational understanding of the complex interactions and drivers of influence across the WEL system. Consequently, priorities drawn from WEF nexus assessment might simply be an artefact of the partial scope of nexus assessment rather than a reflection of major risks to the WEL system and the activities which it supports.

1.2 Nexus assessment in a macroeconomic context

Although the WEF nexus offers a new vantage point to assess the environmental impact of human activity, it appears to overlook the wider burden of human activity in three main ways. First, the WEF nexus conceptualisation of resource interactions within the food system overlooks the primary resource of land in food supply. Since food availability is determined by the primary net productivity of land (a resource stock), it is important to evaluate requirements of the food sector (a resource service) with reference to land availability and quality. Although land has been explicitly included in nexus-based assessment of the food system in a few studies (*cf* Ericksen, 2008; Giampietro, 2014; Hermann et al., 2012; Ingram, 2011; Mukuve & Fenner, 2015a,b) it is not explicitly considered within the majority of nexus scholarship. Second, as cross-cutting analyses of country and sector resource footprints by Bijl et al. (2018), Vivanco et al. (2018a), White et al. (2018) and Vanham et al. (2019) show, feedbacks between water, energy and food supply seldom represent the major source of human influence across the WEL system. In China and the United States Vivanco et al. (2018b) found major water and energy footprints arise from direct and indirect (i.e. embodied) consumption, not feedbacks between water extraction and energy use. As such, analysis of WEF linkages alone provides an insufficiently complete picture of pressures on the WEL system. Third, the WEF nexus focuses principally on competition for natural resources in the food and agricultural sector, as noted by recent reviews of nexus scholarship (*cf* Endo et al., 2015; Galaitsi et al., 2018; Green et al., 2016; Leck et al., 2015; Liu et al., 2015; Simpson & Jewitt, 2019; Wichelns, 2017). As a result, WEF nexus assessment overlooks other drivers of resource shortages and stresses across the WEL system such as competition for natural resources with other final sectors (e.g. manufacturing, services, and extractive industries) and priorities (e.g. environmental flow requirements or urban development) (Taherzadeh et al., 2018).

If nexus scholarship is to provide a useful aid to decision making in the context of resource management, it must first observe fully the global and cross-sectoral scope of national dependence on water, energy and land resources. Considering the nexus between water, energy and land in relation to the various sectors and services it supports would help not only to capture more successfully resource interactions within the context of food production and consumption, but also deepen understanding of resource interdependencies in different sectoral contexts. This multi-sectoral understanding of resource interconnections is critical to identifying systemic priority areas for nexus-based management and further nexus-based assessment. The wider scope of this system boundary of analysis, examined within this thesis, is illustrated in Figure 1.1. In order to elucidate the drivers of domestic resource stresses, and account for the effects of national-level consumption decisions on other territories, resource dependencies across the WEL system must also be examined within the context of the world economy.

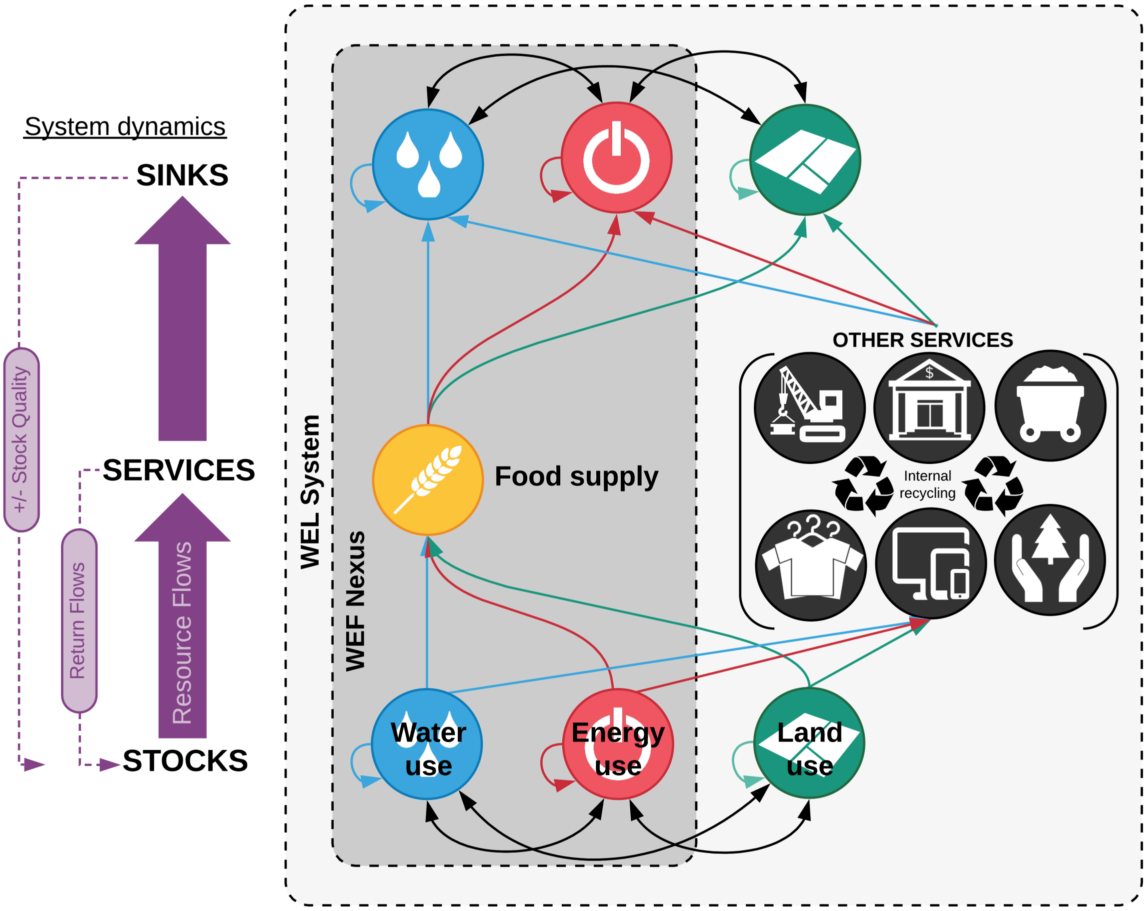


Fig. 1.1 System boundaries of the WEF nexus and WEL system

Conceptual diagram illustrating water-energy-food (WEF) nexus interactions as sub-system of the water-energy-land (WEL) system. Arrows denote relationship(s) between resource stocks (i.e. water, energy and land resources), services (e.g. food supply, construction, clothing, electronic equipment and conservation activities), and sinks (i.e. post-consumption waste flows). Dashed black lines denote system boundaries typically associated with the WEF nexus and WEL system. The restricted scope of the WEF nexus overlooks competition for water, energy and land resources in non-food sectors.

The major sources of pressures across the WEL system are poorly understood owing to the limited study of water, energy and land use pathways within a global and multi-sectoral scope (Taherzadeh et al., 2018). In response, many have called for the development of a unifying methodological framework to evaluate fully, and systematically, the myriad influences across the WEL system (Endo et al., 2015; Galaitsi et al., 2018; Leck et al., 2015; Taherzadeh et al., 2018; Vivanco et al., 2018a). However, the topical focus of nexus-based assessment on WEF interactions and individual case studies limits the application of existing tools and methods of analysis to this end. Most models focus on the manual construction of resource accounts for specific pathways of resource use and transformation which make their flexible application across multiple sectors, supply chains, and spatial scales impractical (Taherzadeh et al., 2018).

Although highly instructive, recent attempts to extend the scope of nexus assessment have been limited to (i) global-scale sectoral priority assessment (*cf* Howells et al., 2013; Vivanco et al., 2018a; Xu et al., 2019), (ii) single country or region analysis (*cf* Bijl et al., 2018; Guan et al., 2019; Munoz Castillo et al., 2019; Owen et al., 2018; White et al., 2018), and (iii) partial analysis of the WEL system (e.g. water-energy, energy-land, or water-land) (*cf* Duan & Chen, 2017; Kirschke et al., 2018; Owen et al., 2018; Vivanco et al., 2018b). Accordingly, a new research paradigm for nexus assessment, which captures the global and multi-sectoral scope of resource use is needed to expose major pathways of water, energy and land use. The widening gap between the rate of policy development and implementation of nexus findings and the completeness of nexus assessment reinforces this need (Stirling, 2015).

1.3 Research objectives

A plethora of assessment approaches and modelling tools has been developed to study the environmental resource footprint of socio-economic systems in an integrated manner. These vary in their sectoral, spatial, and temporal coverage, as well as their integration of the WEL system. Biophysical models, which employ high-resolution satellite resource use data to evaluate the availability and use of natural resources, have dominated the assessment of human influence on the WEL system (Albrecht et al., 2018). Despite offering a detailed characterisation of direct pressures on water, energy and land resources, such approaches do not capture the underlying pathways of resource use in relation to consumption, production and trade activities. The economy, however, offers an increasingly useful entry point to understand and manage the burden of human activity on the WEL system. Economic networks reveal pathways of resource use often not included in biophysical models of human-environment interactions. This allows for a global view of the network of human activity and the way in which interlinkages and trade flows between nations redistribute the environmental burdens of production and consumption. To date, economic models of resource use have received limited attention in the assessment of pressures across the global WEL system (Kling et al., 2017). However, such models have tremendous potential to offer a comprehensive account of resource use across all aspects of human activity, enabling identification of critical consumption and production activities across the WEL system.

This thesis explores how macro-economic methods of resource accounting can be used to broaden nexus assessment, sectorally and spatially, to identify and compare different sources of water, energy and land use, in individual countries and globally. The entry point for the development of such investigation is the ‘resource footprint’, a common yardstick to assess the sustainability of national consumption based on the global demand it imposes on natural resources through complex pathways of production, consumption and trade. Resource footprinting offers a disciplined set of theoretical principles and benefits from widely available economic and environmental accounts which have been underutilised in integrated assessment of pressures across the WEL system (Keairns et al., 2016).

Two methods are employed to evaluate the resource footprint of countries and sectors in relation to water, energy and land use: Material Flow Analysis (MFA) and Multi-Regional Input-Output Analysis (MRIOA). Both methods account for the way in which output is distributed between sectors within the economy and so enable resource use upstream global supply chains to be traced to downstream consumers. As such, they both represent promising avenues for developing a methodological framework for global multi-sectoral nexus assessment. However, the underlying data dependencies of MFA and MRIOA distinguish their suitable application within this thesis. MFA employs detailed physical environmental and commodity accounts which enables accurate accounting of resource use associated with single products (e.g. crops, animal products, or steel) (Galli et al., 2012; Rodrigues et al., 2018; Tukker et al., 2018). Meanwhile, MRIOA evaluates how the demand of a sector or country is distributed throughout the world economy based on financial transactions between sectors and enumerates the production and associated resource requirements arising from these estimated dependencies (Kitzes, 2013). Due to the limited detail of physical environmental and commodity accounts to capture fully country and sector dependencies on water, energy and land resources at a global scale, MFA is poorly suited for the development of a framework for systematic analysis of human influence across the WEL system. This is exemplified by a case study using MFA to conduct nexus assessment in Chapter 3. Meanwhile, MRIOA lends itself to a more comprehensive coverage of resource demand embodied in international supply chains at a sector-wide and economy-wide scale due to the availability of data at this scale. Consequently, MRIOA is the chosen as the principal method of analysis within this thesis.

Three main objectives underpin this thesis research:

1. To identify an appropriate methodological framework for systematically examining human influence across the WEL system;
2. To construct a model which reveals the source and magnitude of human influence across the WEL system; and
3. To advance understanding of critical consumption and production activities to inform the study and management of the WEL system.

1.4 Research questions

Using macro-economic methods of resource accounting to the global WEL system enables more explicit identification of pathways of water, energy and land use from three main sources: (i) international trade, (ii) non-food sectors, and (iii) complex supply networks involving multiple production levels. To date, these sources of resource use have been underexplored within nexus scholarship owing to sub-global study of WEF linkages within the context of upstream production activities (e.g. water, energy and food supply). The current truncation of nexus assessment by spatial, sectoral and supply chain scope offer distinct opportunities for further development of models and empirical analysis to understand pressures across the WEL system.

Accordingly, this thesis examines three related questions to reveal influence of countries and sectors across the global WEL system:

1. What is the contribution of domestic production and international trade to pressures on resources and their use across the WEL system? **Chapters 3 and 4**
2. What are the implications of restricting assessment of the WEL system to food-related sectors? **Chapter 5**
3. How are pressures across the WEL system distributed across global supply networks? **Chapter 6**

1.5 Thesis outline

This thesis begins, in Chapter 2, by examining different methodological approaches to assess pressures across the WEL system empirically. A total of 18 modelling approaches, identified from a review of relevant literature, form the basis of this discussion. Several criteria pertaining to the research questions and objectives of this thesis were used to identify an appropriate framework for systematic, cross-sectoral, and multi-scale assessment of human influence across the WEL system. Biophysical approaches (e.g. geo-spatial analysis, ecosystem-level assessment, and hydrological models) and socio-technical approaches (e.g. infrastructure and capital accounting, firm innovation models, and technology forecasting) reviewed did not exhibit the flexibility and scope demanded by this thesis research due to their inability to trace the pathways of resource use to their source. However, MFA and MRIOA were found to offer a scope of analysis potentially well suited to this research context.

Chapter 3 examines the application of MFA in a case study designed to test this method in the research context. This case study investigates water and land use embodied in soybean trade. International trade of soybeans has increased substantially over recent decades (Taherzadeh & Caro, 2019). This study reveals which countries and sectors are responsible for water use and land area linked to soybean trade. These resource use pathways are estimated by combining physical import and export data and associated environmental accounts from 166 countries during the period 2000-2016. Over this period global water and land area related to soybean trade grew by 298% and 250% respectively. In 2016, this corresponded to one-third of water and land used to grow soybean globally. A sectoral decomposition of this resource demand reveals that animal feed is responsible for around three-quarters of these impacts. This analysis highlights the importance of incorporating trade and multi-sectoral flows into nexus assessment. However, while very detailed individual products can be analysed in this way, data and time constraints involved in using MFA make assessment of global water, energy and land footprints across different production and consumption systems challenging. Indeed, physical environmental and commodity accounts do not yet describe how products, such as soybeans, are distributed throughout different sectors of the economy in a manner which allows pathways of resource use to be easily traced from their origin of production to place of final consumption. Since the demand for goods and services links countries and sectors in complex, globalised supply chains, the absence of adequate physical data to capture indirect and complex resource interdependencies within the world economy renders it unsuitable for the research context of this thesis. In contrast, the superior coverage of MRIOA data within this context offers a more suitable framework to examine the research questions of this thesis in subsequent chapters.

Chapter 4 evaluates the scale and severity of national water, energy and land use dependence from domestic production, regional and remote trade. This chapter begins by outlining the key limitations of resource footprinting. Conventional resource footprinting, whether undertaken by MFA or IOA, produces a single, aggregate value which reflects the overall burden of a country or sector within a given sustainability domain (e.g. water, energy, and land). As a result, the resource footprint of a country or sector does not distinguish its source of production and associated resource risk. This chapter represents the first attempt to assess the risk-related water, energy and land footprint of countries and sectors, and to distinguish the contribution of international trade flows within this context. This is achieved for 189 countries, 19 macro-regions and multiple sectors in the Eora (2019) MRIO database. Linking national consumption to source reveals countries, sectors and regions that are highly exposed, directly (via domestic production) and indirectly (via imports), to over-exploited, insecure, and degraded water, energy, and land resources. However, it is notable that greater exposure to these risks arises via international trade. This assessment indicates the importance of accounting for how pressures across the WEL system are transmitted through global supply chains.

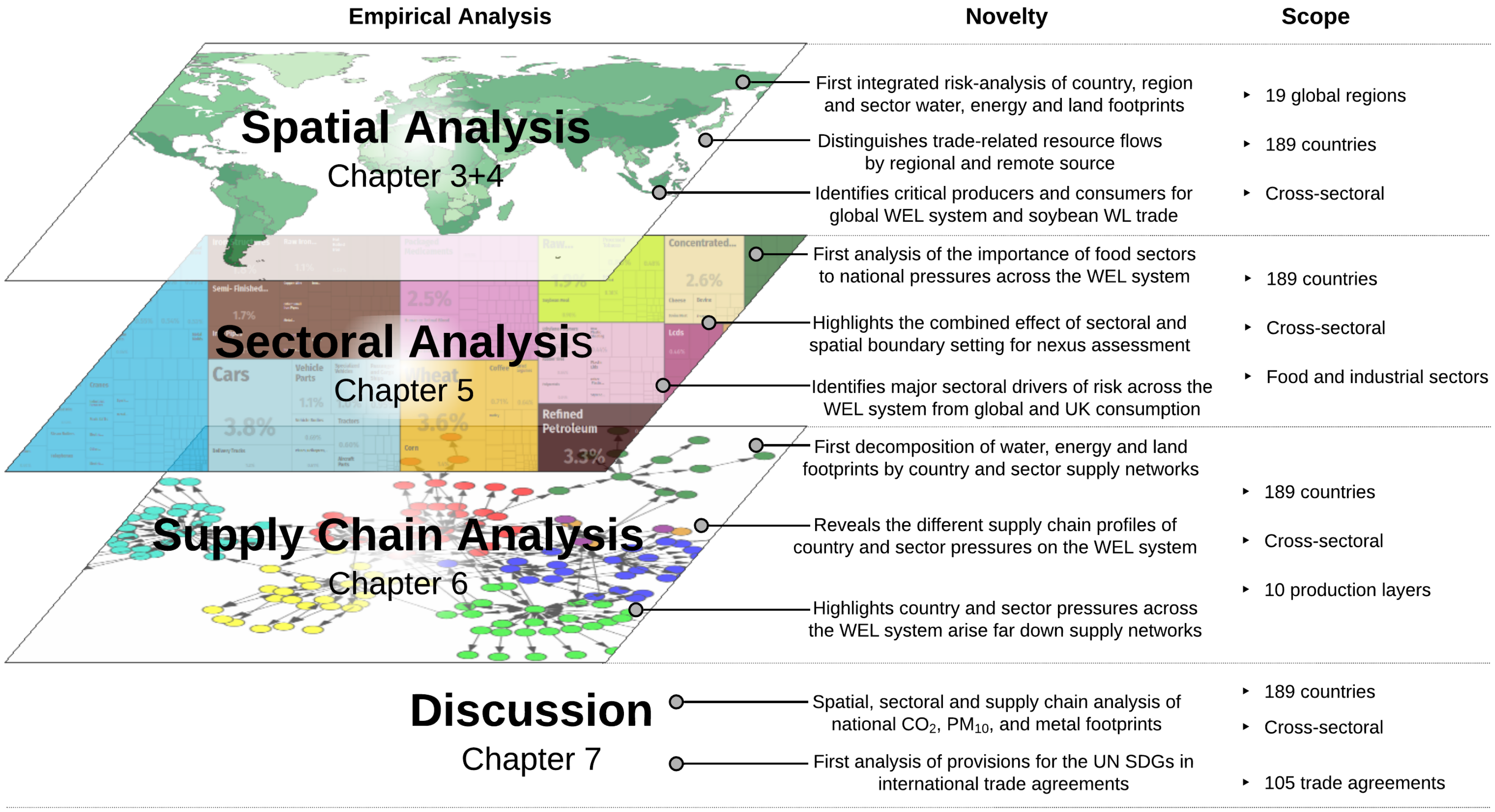
Chapter 5 evaluates the contribution of food and non-food sectors to pressures on resources and their use across the WEL system, in 189 countries. Food sectors are found to be a major, but not sole, contributor to national water and land footprints, but exhibit minor importance in relation to energy use pathways. A similar finding emerges from tracing pathways of high risk water, energy and land use to sectoral source. Other key drivers of pressures across the WEL system include construction, textiles and apparel, transport, and services. Spatial truncation of nexus-based assessment to national boundaries is also shown to ignore major water, energy and land use pathways associated with consumption in food and non-food sectors. These findings highlight the need to encompass multiple sectors and their global impacts in the study of pressures across the WEL system.

Chapter 6 evaluates how pressures across the WEL system are distributed across national and sectoral supply networks. This assessment is conducted for 189 countries and 26 global sectors. Although similar analysis has been undertaken for carbon emissions (*cf* Hertwich & Wood, 2018; Kucukvar & Samadi, 2015; Rodríguez-Alloza et al., 2015), Chapter 6 represents the first supply chain decomposition of pressures on water, energy and land resources at this scale. The resultant analysis reveals that pathways of water, energy and land use in the world economy are mainly indirect, arising from country and sector resource dependencies on immediate (Scope 2) and upstream (Scope 3) producers in their supply network. Moreover, the distribution of water, energy and land use is found to exhibit a high level of variation within and between national and sectoral supply networks. This apparent heterogeneity of country and sector resource use profiles 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.

Lastly, Chapter 7 comments on the contribution of this thesis to the fields of nexus assessment and resource footprinting and its implications for the possibilities of integrated environmental management. A graphical summary of this is provided in Figure 1.2. This discussion chapter then includes an assessment of the limitations associated with the modelling approaches used in this research and how these might be overcome with the application of additional data and methods. Avenues for future research are identified in relation to (i) spatial down-scaling of resource footprint analysis; (ii) improving the sectoral resolution of resource footprint analysis, (iii) forecasting future resource pressures; and, (iv) the development of indicators and data visualisation techniques which help to communicate nexus assessment in an accessible and actionable way. This is followed by a reflection on the potential mechanisms required to translate the findings of this thesis into practical recommendations for policy.

By prioritising flexibility, the methodological framework developed within this thesis is capable of examining human influence on the environment from the perspective of multiple countries and sectors, and in relation to changing policy priorities, questions and indicators. The UK is used as a case study in Sections 4.3.3, 5.5 and 6.7 to demonstrate the data arising from, and potential application of, findings within this thesis. The open-access publication of data and analysis associated with all analysis within this thesis, available at (Taherzadeh, 2020), will enable similarly rich profiles to be drawn across the countries and sectors within the Eora (2019) database.

The strict reliance on open-access datasets and publication of programming code used within this thesis (Appendix A) enables the replication, use and further development of this analysis. It is hoped that through careful construction, the data used and analysis undertaken for this research can be used by researchers, national governments and industry to comprehend the scale of human influence on global water, energy and land resources and the priorities for their sustainable management.



Spatial Analysis (Chapter 3+4)

- First integrated risk-analysis of country, region and sector water, energy and land footprints
- Distinguishes trade-related resource flows by regional and remote source
- Identifies critical producers and consumers for global WEL system and soybean WL trade

Scope:
- 19 global regions
- 189 countries
- Cross-sectoral

Sectoral Analysis (Chapter 5)

- First analysis of the importance of food sectors to national pressures across the WEL system
- Highlights the combined effect of sectoral and spatial boundary setting for nexus assessment
- Identifies major sectoral drivers of risk across the WEL system from global and UK consumption

Scope:
- 189 countries
- Cross-sectoral
- Food and industrial sectors

Supply Chain Analysis (Chapter 6)

- First decomposition of water, energy and land footprints by country and sector supply networks
- Reveals the different supply chain profiles of country and sector pressures on the WEL system
- Highlights country and sector pressures across the WEL system arise far down supply networks

Scope:
- 189 countries
- Cross-sectoral
- 10 production layers

Discussion (Chapter 7)

- Spatial, sectoral and supply chain analysis of national CO_2, PM_{10}, and metal footprints
- First analysis of provisions for the UN SDGs in international trade agreements

Scope:
- 189 countries
- Cross-sectoral
- 105 trade agreements

Fig. 1.2 Summary of thesis scope and novelty of analysis

Chapter 2

Methodological approaches to nexus assessment

> The risk is that containing this territory, however loosely, constrains it instead — and that the nexus becomes the focus of the analysis, rather than a natural consequence of studying the supporting problems
>
> ---
>
> *Editorial, Nature (2016)*

2.1 Introduction

In recent years, several assessment and modelling approaches has been developed to study the environmental resource footprint of socio-economic systems in an integrated manner. Section 2.2 presents a review of key modelling approaches within this context. Research gaps, priorities, and methodological principles identified within this review are discussed within the context of the thesis objective: to identify an appropriate methodological framework for systematically examine human influence across the WEL system. Insights from this review, summarised in Section 2.2.4, and those from scoping analysis undertaken in Chapter 3, suggest Multi-Regional Input Output Analysis (MRIOA) is a suitable framework of analysis for this research. Section 2.2.5 outlines the methodological principles of MRIOA, the main database used in this thesis, and the related computational requirements of its analysis. Additional data and analytical procedures pertaining to assessments undertaken for this thesis are detailed in their respective chapters.

2.2 Review of nexus modelling approaches

This section provides a review of resource assessment and modelling approaches with extant or potential capabilities to undertake nexus-based assessment of the global WEL system. modelling approaches which focus on a single dimension of the nexus and methodologically prohibit analysis of coupled resource interactions are excluded from this review. This review concludes by identifying an appropriate methodological approach within this context. In total, eighteen modelling approaches, summarised in Table 2.2, were analysed. These modelling approaches were sourced from several areas of literature, including *inter alia* WEF nexus assessment, resource footprinting, earth systems modelling, and ecological economics, and were selected for further review based on their potential application to the research questions (Section 1.4) and objectives (Section 1.3) of this thesis.

Table 2.1 Modelling approaches reviewed

Modelling approach	Background	Reference
Brown-Green Capital Model	A macroeconomic model developed to analyse the lLock-in and path dependence of the global economy to fossil-fuel reliance and required investment to ‘lock-out’ towards a lower-energy economy	(Kemp-Benedict, 2014)
Climate, Land-use, Energy, and Water (CLEW) Model	Multi-module tool which enables flexible application of nexus-based assessment within a variety of scenarios	(Howells et al., 2013)
FAO’s Nexus Assessment Methodology	Conceptual framework designed to inform the appraisal of resource policies based on existing water, energy, land, and climate sustainability indicators	(Flammini et al., 2014)
Footprint Family of Indicators	A methodological approach to harmonise existing carbon, ecological, and water footprint to economic accounts to enabled integrated assessment of production and consumption systems	(Ewing et al., 2012; Galli et al., 2012)

Continued on next page

Table 2.1 – continued from previous page

Modelling approach	Definition	Reference
Foreseer Tool	A scenario analysis tool which includes natural resource supply, transformation, and use, as well as the ways in which they affect each other, to enable systematic nexus-based assessment of production and consumption systems	(University of Cambridge, 2013)
InVEST: Integrated valuation of ecosystem services and tradeoffs	Decision support tool developed to evaluate changes in ecosystems service delivery arising from utilisation of natural resources	(Tallis et al., 2011)
LowGrow Model	A dynamic, macroeconomic simulation model developed to forecast the effects of low (and no) growth pathways on social (low levels of unemployment) and environmental (low greenhouse gas emissions) objectives	(Victor & Rosenbluth, 2007)
Modelling System for Agricultural Impacts of Climate Change (MOSAICC)	Tool to evaluate crop production systems in response to changes in climate, water conditions, and forest resources, and national economic output	(FAO, 2015)
Modelling the balanced transition to a sustainable economy	A simple mathematical model of the economy developed to simulate the decoupling between economic growth and carbon emissions under different policy scenarios	(Bastin & Cassiers, 2013)

Continued on next page

Table 2.1 – continued from previous page

Modelling approach	Definition	Reference
Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIAEM)	Flexible model enables the analysis of resource availability and use between the environment, the economy, and society, at multiple scales to assess the compatibility of different consumption patterns with environmental boundary conditions	(Giampietro, 2014)
Multisectoral Macroeconomic model of the German Economy (MMG)	A macroeconomic model developed to analyse dematerialisation of the economy via the transition of the economy from production of goods to the production of services	(Kronenberg, 2010)
Soil and Water Assessment Tool (SWAT)	Watershed modelling tool developed to simulate land management practices on water availability and quality	(Arnold et al., 2012)
Stock-Flow-Fund Ecological Macroeconomic Model	A hybrid physical-financial model developed to simulate trajectories of interactions between the ecosystem, financial system, and the macroeconomy	(Dafermos et al., 2017)
TIMES model	Model enables the exploration of different energy futures for a single or multiple region energy system based on user-defined constraints (i.e. end-user requirements, technologies and fuel choices, and prices).	(Loulou et al., 2016)

Continued on next page

Table 2.1 – continued from previous page

Modelling approach	Definition	Reference
Water-Energy-Food (WEF) Nexus Tool 2.0	Analytical framework and decision making support tool for undertaking nexus-based analysis within a food systems context	(Daher & Mohtar, 2015)
WEAP-LEAP	Analytical tool for enabling nexus-based scenario-analysis and forecasting of water-energy-emissions interactions at a waster-basin scale	(SEI, 2012)
World Trade Model	Dynamic macroeconomic model of global trade which identifies optimal paths for production and consumption systems based on comparative advantage of world prices, resource scarcity, and international trade flows	(Duchin, 2005; Duchin & Levine, 2016)

This review addresses several gaps in previous reviews of nexus assessment approaches. First, by studying the explanatory power of nexus assessment approaches within the context of the global WEL system, this review offers a more holistic assessment of their potential application. Previous appraisals have considered the effectiveness of assessment approaches only in relation to WEF linkages (*cf* Albrecht et al., 2018; Endo et al., 2015; Keairns et al., 2016; Kling et al., 2017; McGrane et al., 2019; Namany et al., 2019). Second, many of the previous reviews of nexus methods merely catalog nexus-based tools and approach (*cf* Albrecht et al., 2018; Brouwer et al., 2018; Endo et al., 2015) instead of explain their weaknesses and applications in relation to different scales of nexus assessment, as this review attempts to. Lastly, this review explores the *potential* application of nexus assessment approaches and not only their *existing* applications - as in McGrane et al. (2019), Endo et al. (2015), Albrecht et al. (2018), and Brouwer et al. (2018) - in order to assess the flexibility of their application to the research questions of this thesis.

To aid cross-comparison, nexus modelling approaches are discussed in relation to three dimensions relevant to the study of human influence across the WEL system. First, Section 2.2.1 explores model boundary setting in relation to (i) dimensions of the WEL system, (ii) sectoral coverage, (iii) spatial scope, and (iv) units of attribution for resource use. Second, Section 2.2.2 distinguishes the different methodological principles of nexus modelling approaches and their suitability within the context of the proposed research within this thesis 2.2.2. Lastly, Section 2.2.3 summarises the different outputs of nexus modelling approaches (e.g. indicators, visualisation methods and tools).

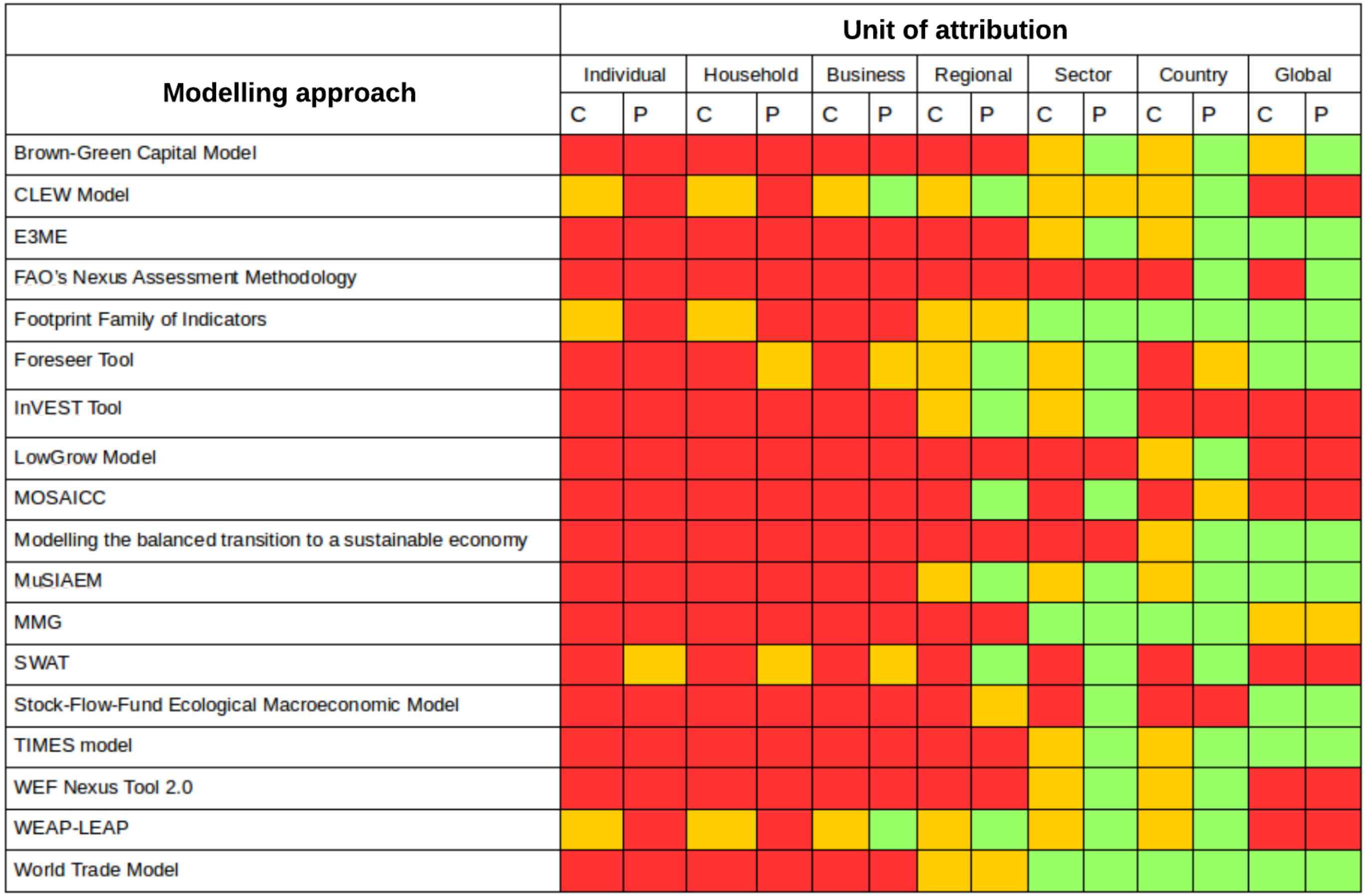
2.2.1 Boundary setting

The coverage of nexus dimensions within resource assessment and modelling approaches largely reflects the conceptual focus of nexus scholarship on the study of (i) coupled water-energy resource interconnections (WEAP-LEAP) and (ii) water-land (SWAT Tool) and water-energy-land (CLEW model; WEF Nexus Tool 2.0; MOSAICC; FAO's nexus methodology; InVEST) interactions within the context of food system and ecosystem service sustainability. A further group of models coalesce around the problem of decarbonisation and climate change mitigation and focus on assessment of economic and energy transitions to this end (TIMES model; Brown-Green Capital Model; MMG; Modelling the balanced transition to a sustainable economy; LowGrow model; E3ME Model). Meanwhile, a group of economy-wide resource footprinting models demonstrate coverage of human influence across the entire WEL system (Foreseer Tool; Stock-flow-fund ecological macroeconomic model; Footprint Family of Indicators; World Trade Model; MuSiaSEM). The topical focus of nexus modelling approaches is symptomatic of the importance assigned to relational pathways of resource use within the nexus concept (e.g. water required in energy production or energy required for crop irrigation). Indeed, environment-economic models which aim to capture more fully water, energy and land use pathways tend to be guided not by the nexus concept, but a broader commitment to analysis of complex systems.

The sectoral coverage of nexus-based assessment modelling approaches is of central importance to the objective of developing a systematic understanding of pressures across the WEL system. Several modelling approaches reviewed focus narrowly on natural resource used within the agricultural and food production – CLEW model , WEF Nexus Tool 2.0, WEAP-LEAP, SWAT, MuSIASEM, and MMG). In contrast, several economy-wide models are unable to distinguish individual sectors and their resource-related footprints, due to their highly aggregated treatment of national economic output (Stock-Flow Fund Ecological Macroeconomic Model; Brown-Green Capital Model; Modelling the balanced transition to a sustainable economy; LowGrow Model). Consequently, the only models capable of enabling nexus-based assessment of resource use across multiple production and consumption systems are those which explicitly use multi-sectoral resource use data, such as the Foreseer Tool, TIMES model, and the Footprint of Family Indicators.

Nexus modelling approaches also vary in their geographical focus and therefore the boundary of their assessment of resource use. MOSAICC, the InVEST Tool, the SWAT tool, the CLEW tool, and WEAP-LEAP were developed to undertake nexus-based assessment at a sub-national scale, with attention to accurate high resolution modelling of resource availability and its within-country variation. These analyses are enabled by use of gridded geospatial data on water and land availability, sensitive ecological sites, and down-scaled observations of climate impacts on water and land availability. The remaining modelling approaches focus on nexus-based assessment at national and supra-national scales. The spatial resolution of these models is often more coarse than models focused on sub-national resource assessment, however they enable environmental footprinting of consumption and production activity across global supply chains. Although a few select models demonstrate flexible application of nexus-based assessment within sub-national and global contexts – The Foreseer Tool and MuSIAESEM – they do not enable explicit linkage of resource use between these scales. A knowledge gap within nexus-based assessment, and resource accounting more generally, is to understand how resource-related pressures are transmitted through consumption and production systems between local, national, and global scales (Croft et al., 2018).

The sectoral and spatial boundaries of nexus assessment tools determine their ability to attribute responsibility for resource use at relevant scales of resource management. Figure 2.1 illustrates how modelling approaches vary in their potential to attribute resource use to actors at different spatial scales. Attribution of resource use to countries or sectors is determined by two main approaches: Production-based Accounting (PBA) and Consumption-based Accounting (CBA). PBA of resource use evaluates the direct resource burden associated with production in a given country or sector. This establishes a boundary - territorially for countries and operationally for sectors - in terms of the scope of country and sector resource use being evaluated. The implications of such boundary setting are two-fold. First, PBA does not account for the resource use a country imposes beyond its national borders, on other territories, through international trade *or* the resource demand of a sector upstream its supply chain. Second, PBA assigns full responsibility for resource use associated with country or sector production irrespective of whether this is destined for consumption in other territories or sectors. For example, PBA of China's carbon emissions would imply it is fully responsible for the carbon emissions associated with its production of mobile phones even if half of these were exported for final consumption in Europe and North America. However, PBA would not capture the carbon emissions associated with products China imports for final consumption, such as raw materials, machinery, electronics, and motor vehicles which are produced in other countries (Davis & Caldeira, 2010; Guan & Reiner, 2009). Equally, at a sectoral level, PBA of greenhouse gas (GHG) emissions associated with soybean production would not assign responsibility for soybean-related GHG emissions (e.g. caused by deforestation) to downstream consumption sectors, such as the livestock sector or bio-energy sectors, nor would it determine soybean production to be responsible for the GHG emissions embodied in fertilisers, machinery and transportation used to grow, harvest and distribute the crop. In contrast, CBA captures both the direct and indirect (i.e. embedded and traded) resource use of a countries or sectors, assigning responsibility for upstream production in global supply chains to downstream final consumers. In effect, CBA enumerates the full resource burden of an economic unit which is important given the cross-sectoral and multi-regional dependencies and impacts of individual, sectoral, and national activity.



Modelling approach	Unit of attribution													
	Individual		Household		Business		Regional		Sector		Country		Global	
	C	P	C	P	C	P	C	P	C	P	C	P	C	P
Brown-Green Capital Model	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟧	🟩	🟧	🟩
CLEW Model	🟧	🟥	🟧	🟥	🟧	🟩	🟧	🟩	🟧	🟧	🟧	🟩	🟥	🟥
E3ME	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟧	🟩	🟩	🟩
FAO's Nexus Assessment Methodology	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟩
Footprint Family of Indicators	🟧	🟥	🟧	🟥	🟥	🟥	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩
Foreseer Tool	🟥	🟥	🟥	🟧	🟥	🟧	🟧	🟩	🟧	🟩	🟥	🟧	🟩	🟩
InVEST Tool	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟧	🟩	🟥	🟥	🟥	🟥
LowGrow Model	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟥	🟥
MOSAICC	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟥	🟧	🟥	🟥
Modelling the balanced transition to a sustainable economy	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟩	🟩
MuSIAEM	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟧	🟩	🟧	🟩	🟩	🟩
MMG	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟧	🟧
SWAT	🟥	🟧	🟥	🟧	🟥	🟧	🟥	🟩	🟥	🟩	🟥	🟩	🟥	🟥
Stock-Flow-Fund Ecological Macroeconomic Model	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟥	🟩	🟥	🟥	🟩	🟩
TIMES model	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟧	🟩	🟩	🟩
WEF Nexus Tool 2.0	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟩	🟧	🟩	🟥	🟥
WEAP-LEAP	🟧	🟥	🟧	🟥	🟧	🟩	🟧	🟩	🟧	🟩	🟧	🟩	🟥	🟥
World Trade Model	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩

Fig. 2.1 Unit(s) of attribution enabled by nexus-based assessment

A gap assessment of the different unit(s) of scale and actor attribution for resource use enabled by the 18 modelling approaches reviewed. Green shading reflects modelling approaches which enable complete resource accounting at a given scale; orange shading indicates partial or potential resource attribution; and, red refers to the inability to attribute resource flows to a given scale. Consumption-based and production-based footprint capabilities are denoted by 'C' and 'P' respectively

Production-based assessment of individual, household, and business resource consumption is challenging in the absence of data. In the case of individuals and households, resource extraction and use is non-reported since it (i) features in the informal economy or (ii) is aggregated by statistical agencies to a municipal level. However, the consumptive footprint of individuals from sectors across the domestic and world economy can be inferred by other methods which use national-level statistics (i.e. per capita figures and regional weightings based on sub-national economic accounts). For businesses, resource extraction and use data are often proprietary, poorly reported (in the case of corporate sustainability reporting framework), and highly aggregated within national accounts (Taherzadeh & West, 2016). Consequently, nexus-based assessment of household consumption and business activities requires a wealth of information that is not currently available.

The majority of modelling approaches reviewed (15 out of 18) were capable of evaluating the production-based resource footprint of individual sectors and countries. However, due to the incomplete treatment of upstream resource use in supply chains, few modelling approaches demonstrated the ability to evaluate the consumptive resource footprint of sectors and countries. Of the models reviewed, only the Footprint Family of Indicators, MMG, and World Trade Model, and the Foreseer Tool offer the capability to examine consumption-based resource footprints for countries and sectors.

2.2.2 Methodologies of nexus modelling approaches

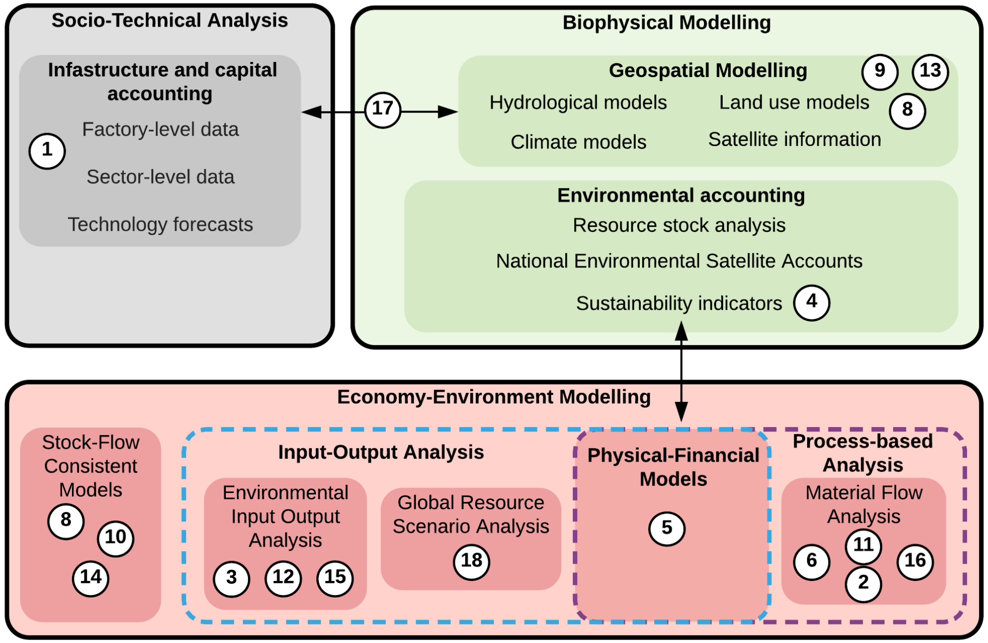
A range of methodological approaches are used by the modelling approaches reviewed. These can be broadly defined within three categories: Socio-Technical Analysis, Biophysical Modelling, and Economy-Environment Modelling. Figure 2.2 illustrates the coverage of modelling approaches reviewed within this schema.

Socio-Technical analysis within the context of nexus-based assessment supports environmental footprinting of infrastructure and capital based on different water, energy, and land use scenarios. The main tool in this category is the Brown-Green Capital Model, developed to analyse the impacts of investment on lock-in and path dependence of infrastructure to fossil-fuel or low-carbon energy use.

Biophysical Modelling includes Geospatial Modelling and Environmental Accounting. Geospatial Modelling approaches (SWAT, InVEST Tool, CLEW Model, WEAP-LEAP tool, and MOSAICC) were all developed within a Geographical Information Systems (GIS) framework in order to evaluate resource availability at a high spatial resolution, accounting for their heterogeneity at sub-regional scales. Environmental Accounting modelling approaches directly utilise national-level data on resource use at sectoral and economy-wide scales. The indicator-led approach proposed by the FAO's Nexus Assessment Methodology exemplifies this.

Environment-Economy Modelling include three main families of resource accounting approaches: Stock-Flow Consistent Modelling, process-based modelling, and Input Output Analysis (IOA). Several models reviewed (LowGrow, Modelling the transition to a balanced economy, Stock-Flow Fund Ecological Macroeconomic Model) adopt a Stock-Flow Consistent approach to modelling resource use at a macroeconomic scale. This method uses behavioural rules alongside monetary accounts to achieve a consistent accounting framework of financial stocks and flows within all sectors of the economy (Caverzasi & Godin, 2015). Within the context of resource accounting, Stock-Flow Consistent models can be used to measure feedbacks between fiscal and monetary policies, financing, and resource-use within the economy. However, this method often uses averaged figures for the resource intensities of different sectors and treats the world economy as a highly aggregated system, preventing effective calculation and attribution of individual resource consumption.

The other two Environment-Economy Modelling approaches identified, process-based modelling and IOA, share a common aim to account for all resource flows within a defined production and consumption system (e.g. a sector, national economy, or the world economy). However, these methods differ in their practical application arising from choices made in relation to the availability of data on physical resource flows. Material Flow Analysis (MFA) is a process-based Modelling approach which constructs a self-consistent database of resource inputs and outputs to follow and quantify the flow of materials within a defined system, over a specified period of time. Several models reviewed use MFA: The Foreseer Tool, MuSIAEM, and the WEF Nexus Tool 2.0. A core principle of MFA is that mass and energy must be conserved through the various transformations of resource stocks (e.g. water, energy, and land) leading to the final services, and their associated waste products from the economy to the environment. As such, MFA highlights both demand- and supply-side opportunities for improving material resource efficiency (Curmi et al., 2013a).



Ref	**Modelling approach**
1	Brown-Green Capital Model
2	CLEW Model
3	E3ME
4	FAO's Nexus Assessment Methodology
5	Footprint Family of Indicators
6	Foreseer Tool
7	InVEST
8	LowGrow Model
9	MOSAICC
10	Modelling the balanced transition to a sustainable economy
11	MuSIAEM
12	MMG
13	SWAT
14	Stock-Flow Fund Ecological Macroeconomic Model
15	TIMES MODEL
16	WEF Nexus Tool 2.0
17	WEAP-LEAP
18	World Trade Model

Fig. 2.2 Typology of modelling approaches for nexus assessment

However, limited data availability and the complexity involved in manually constructing material flows accounts makes the process of tracing pathways of water, energy and land use in the world economy extremely challenging. Numerous layers of manufacture and processing are involved in the transformation of resources to final goods and services (Kitzes, 2013). Currently, physical consumption, production and trade accounts do not readily explain how resources are embedded in country and sector supply chains. This limitation is less applicable to the representation of production and consumption systems at a highly aggregated scale, such as the modelling of global production and consumption systems in the Foreseer Tool (*cf* Bajželj et al., 2014; Cullen et al., 2012; Lupton & Allwood, 2016). However, tracing the upstream resource pressures to downstream final consumption explicitly, at the level of a national economy and its respective sectors, is not practically feasible given current physical production, consumption, and trade accounts. These limitations make MFA and other process-based modelling approaches (e.g. Life Cycle Analysis) susceptible underestimating resource use embodied in consumption and production systems by restricting their analysis to a limited number of production levels in supply networks (Schaffartzik et al., 2015). Within the assessment of international virtual (i.e. indirect) water trade between countries, Lenzen et al. (2013a) demonstrate that truncated assessment of water resource flows using MFA results in a 50% underestimate in the evaluation of regional and sectoral water footprints. Incomplete mapping of resource flows between sectors can also result in further issues around the approximation and attribution of resource pressures arising from economic activity. First, double counting of resource use can result from inconsistent specification of producing and consuming entities within the world economy (Lenzen, 2008a). This could erroneously suggest the consumption of a sector or a country is overstepping a given planetary boundary when in fact activities are compatible with such a limit. Second, use of bilateral physical trade statistics (e.g. UN Comtrade and FAO) can lead to mis-identification of the provenance of raw commodities where resource extraction and pressures occur (Hubacek & Feng, 2016). For instance, if soybeans were grown in Brazil and shipped to China for processing, then exported from China to the UK, bilateral trade statistics would identify China as the producing nation, not Brazil (Hubacek & Feng, 2016) .

IOA attempts to understand the structure of the economy in terms of the interdependencies between sectors and households (Suh, 2009). The field of Input-Output Economics was founded by Wassily Leontief who conceived of a disciplined approach, introduced in Section 2.2.5, to formulate and analyse national economic accounts in order to understand fully the relationships (direct and indirect) between producers and consumers across complex supply chains (Miller & Blair, 2009). This foundational work, developed in the 1960s, supported a growing number of studies designed to understand the broader interactions between the economy, society, and environment, under the influence of existing and potential trajectories of industrial, technology and policy development (*cf* Carter, 1966, 1974; Ghosh, 1964; Isard, 1951; Leontief, 1967, 1970, 1977, 1983, 1986; Leontief & Strout, 1963).

The process of using IOA to assess the resource footprint of country and sector consumption, explained in Section 2.2.5, 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 & Feng, 2016).

Several complementary methods have descended from IOA, such that it is preferable to consider input-output economics as a family of modelling approaches, techniques and assumptions. Social Accounting Matrices (SAMs) and Computable General Equilibrium (CGE) models are two such variants of IOA which are widely applied within the context of resource use modelling. In addition to product flows contained within IO accounts, SAMs capture the distribution of income and expenditure within the economy in order to show the entire circular flow of money between households, sectors and government (Pyatt, 1985). By explicitly identifying links between incomes in the economy, SAMs offer a way of distinguish consumption patterns and associated resource impacts associated between different socio-economic and not just in relation to national consumption as is typical of conventional IOA (Allan et al., 2007). IO tables and SAMs provide the basis of CGE models which explicitly relaxes the fixed-price assumption employed in IOA to solve both market prices and quantities within the economy simultaneously (Suh, 2009). This dynamic nature of CGE models enables the assessment of exogenous factors, such as demographic change or productivity shifts, on rates of resource availability and depletion (Beghin et al., 2006). Although, the inclusion of additional parameters in CGE models rely on further assumptions concerning utility maximisation and market price equilibrium and elasticities which potentially undermine their usefulness in empirical analysis (West, 1995). Several models reviewed employed variants of IOA - E3ME (CGE), MMG (SAM) and TIMES (CGE), and Footprint Family of Indicators (IOA). Within the context of this thesis research, the additional analytical capabilities of SAMs and CGEs were not deemed necessary due to the non-dynamic nature of research questions being examined (see Section 1.4).

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, detailed in Section 2.2.5. Lenzen et al. (2004) distinguish three main approaches to MRIOA, which are illustrated in Figure 2.3: (i) autonomous regions, (ii) uni-directional trade, and (iii) multi-directional trade. 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, detailed in Section 2.2.5. Lenzen et al. (2004) distinguish three main approaches to MRIOA, which are illustrated in Figure 2.3: (i) autonomous regions, (ii) uni-directional trade, and (iii) multi-directional trade.

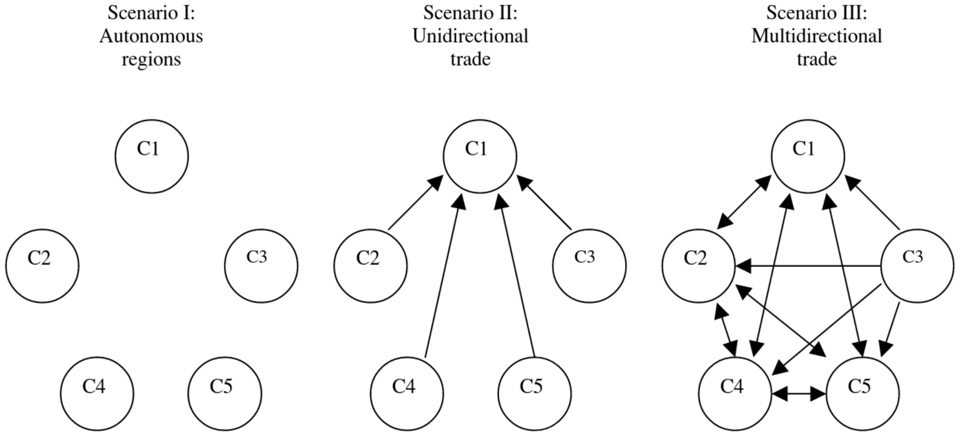


Fig. 2.3 Systems of trade accounting in MRIOA
Conceptual diagram reproduced from Lenzen et al. (2004) illustrating the different treatments of producer technology in multi-regional input output trade analysis. Scenario 1 assumes imported commodities are produced using domestic recipes. Scenario 2 distinguishes national and non-national differences in producer recipes. Scenario 3 (adopted within this thesis) recognises the unique production recipes of each country in a multi-lateral trade network.

Within the autonomous regions modelling scenario, imported commodities are assumed to be produced using domestic recipes. This implies that foreign industries exhibit factor multipliers that are identical to those of the domestic industries. However, this assumption of homogeneous production conditions can introduce errors into calculations of the environmental impacts embodied in commodities produced upstream for final consumption (Lenzen et al., 2004). The uni-directional trade modelling approach accounts for national differences with regard to production inputs and resource efficiency. However, as with the autonomous regions scenario, no feedback trade loops are accounted for within the uni-directional trade scenario. The multi-directional trade scenario follows a multi-regional approach and traces resources through the various feedback trade loops from production to final consumption, not just for the country of dispatch (as in the first two scenarios). Many multi-regional do not explicitly cover the entire world, but separate countries of interest for analysis, and model the remainder (i.e. "rest of the world") (see Section 2.3). Of the models analysed, the MMG model adopts a unidirectional approach in its analysis of the material footprint of the German economy using a single national input-output table, whereas the E3ME, TIMES, World Trade Model, and Footprint Family of Indicators follow a multi-directional trade approach which allows flexible analysis of the environmental footprint of different countries and their sectors within a global context.

In practice, IOA approaches rely on several assumptions to gain a deeper understanding of resource flows. IOA is based on a static representation of spatial and economic relationships between producers and consumers within the world economy. However, in reality, dependencies between sectors are dynamic and constantly changing owing to price fluctuations, demand- and supply-side pressures. The snapshot of resource flows IOA provides is therefore a blunt tool for observing sub-annual changes in resource pressures as a result of changing sourcing structures, consumption patterns, and production activity. Linked to this, IOA uses market prices to establish dependencies between sectors and in turn, the direction and magnitude of resource flows; since prices fluctuate, IOA is susceptible to under/overestimation of the environmental footprints of sectors and countries. Further limitations of MRIOA are examined within the context of the different assessments in this thesis and can be found in Sections 4.4, 5.6, 6.7. Sections 7.2 and 7.3 provide an overall reflection on the role of MRIOA in nexus assessment and Section 7.4 highlights future research avenues for its improvement.

Developing a framework capable of enabling nexus-based assessment of environmental footprints across multiple sectors, and from different country perspectives, is data-intensive, as demonstrated in Section 2.6. Of the nexus-based assessment modelling approaches reviewed, the majority are heavily reliant on model inputs from manual data collection, processing, and complex processes of allocation. As discussed, such a requirement invariably results in either aggregation or boundary setting of analysis at geographical or sectoral scales which introduces truncation errors. As such, process-based modelling methods, such as MFA, appear ill-suited to global, multi-sectoral nexus-based assessment. In contrast, the superior coverage of MRIO data (see Section 2.3) makes IOA uniquely suited to the macro-scale assessment demanded by this thesis research.

2.2.3 Model outputs

Understanding how complex information can be communicated to decision-makers is a challenge that lies between science and policy (Sutherland et al., 2012). This challenge is particularly salient to nexus based-assessment, where there is a need to communicate analysis of water, energy, and land resource use associated with resource policies and scenarios in a straightforward, comparable, and actionable way. Nexus-based assessment modelling approaches respond to this need in various ways. In terms of environmental indicators, all modelling approaches reviewed report information on the individual environmental footprints of resource policies (according to their coverage of nexus-dimensions) using conventional units for water use (m^3), land use (hectares), energy use (Watts/Joules), and greenhouse gas emissions (tonnes, in individual or CO_2 equivalent units). Some modelling approaches calculate and report several indicators for a given nexus dimension. The Footprint Family of Indicators framework reports three separate indicators for water use (blue, green, and grey water[1]). Other modelling approaches focus on indicators which explicitly quantify the coupled resource relationships between natural resources. The WEF Nexus Tool 2.0 disaggregates energy use by (i) energy required for water desalination, treatment and pumping and (ii) energy-related required for tillage, fertiliser production, harvest and local transport related to food production; and, the FAO's nexus assessment methodology recommends a

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[1] Blue water refers to water sources from surface or groundwater resources. Green water refers to precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants. Grey water is a hypothetical measure of the volume of freshwater required to assimilate pollutants to meet specific water quality standards

suite of 67 indicators to evaluate nexus linkages around bioenergy (n=6), energy requirements for irrigation (n=12), hydropower (n=8), water desalination for agriculture (n=9), energy subsidies for agriculture (n=16), and food production facility (n=16). Both the WEF Nexus Tool 2.0 and the FAO's nexus assessment methodology also recommend use of aggregation and weighting of such indicators in relation to their policy importance to evaluate the trade-offs and co-benefits of different resource policy interventions across the WEL system.

Data visualisation is another important output of nexus-based assessment modelling approaches in terms improving communication of analysis to decision makers by highlighting resource interactions in a transparent and engaging manner (Bajzelj et al., 2016). Several modelling approaches include an interactive user-accessible platform for simulating different resource scenarios. WEAP-LEAP uses a GIS-based programme developed to enable watershed mapping of energy, greenhouse gas emissions, and water abstraction. The InVEST tool adopts a similar approach, although it focuses on mapping production units according to ecosystem risks. The WEF Nexus Tool 2.0 depicts net changes in domestic and 'imported' resource use arising from user-defined changes in domestic food self-sufficency for a variety of food products. The Foreseer tool uses Sankey diagrams to convey resource interactions between water, energy, land, and greenhouse gas emissions across production and consumption systems. Sankey diagrams depict the direction and magnitude of resource flows from resource stocks, in this context via their transformation to services and their eventual emission to resource sinks.

The FAO's Nexus assessment methodology recommends the use of a radar graph to simplify cross-comparison of policy measures based on their resource impact and the criticality of different resources. These bear some resemblance to the planetary boundaries diagrams initially conceived by Rockström et al. (2009) and later extended by Raworth (2017) to represent human activity in relation to environmental and social limits. Such diagrams enable straightforward comparison of different resource situations between different sectors and scales and under alternative policy measures.

2.2.4 Summary

Several observations emerge from this review of modelling approaches for nexus-based assessment. First, effective and policy-relevant nexus-based assessment cannot be achieved within the disciplinary silos of biophysical modelling or socio-technical analysis. Environmental systems models do not analyse resource availability and use within the context of the supply chains along which they propagate. Such information is key to identifying, and attributing responsibility for, the resource-related pressures that sectors and countries face and the exploitation they drive. Second, the interconnections between production and consumption systems within the world economy are inherently complex and cannot be meaningfully understood, within the context of this thesis research, using physical environmental and commodity accounts alone. This limitation is exposed in Chapter 3 which employs MFA to assess water and land use embodied in international soybean trade. However, the use of MRIO data, which captures more comprehensively the sectoral interdependencies between sectors and economies, does offer a suitable basis for exploring the global and cross-sectoral scope of human influence on the WEL system. Third, the explanatory power of nexus-based assessment can be significantly enhanced by the use of appropriate model outputs, such as indicators and visualisation modelling approaches. The next section of this chapter implements the learning outcomes from this review by proposing a framework, based on MRIOA, for assessment of country and sector influence on the global WEL system.

This section outlines the procedural steps involved in the development and implementation of MRIOA which serves as the principal methodological framework for the research reported in this thesis. An overview of the underlying methodological principles of MRIOA is provided in section 2.2.5. Section 2.2.6 summarises the MRIO databases available and justifies why the Eora (2019) database is used. Section 2.2.7 explains the types of data visualisation used within the thesis. Lastly, Section 2.2.8 conveys the computational requirements of the analysis reported within this thesis.

2.2.5 MRIO Analysis

This section outlines the accounting and methodological approach underlying MRIOA. The proposed nomenclature and notation is provided in Table 2.2. Authors within the MRIO community follow different naming conventions and schema (*cf* Kitzes, 2013; Munksgaard et al., 2008; Peters et al., 2011). Within this thesis the conventions in Lenzen et al. (2012a), Ewing et al. (2012) and Galli et al. (2012), and Peters (2008) are used for their simplicity.

Table 2.2 Notation for MRIOA

Symbol	Meaning
$\mathbf{A}$	Direct requirements matrix: a set of coefficients which describes the production and consumption relationships between all sectors within a defined system to estimate the required production inputs of all other sectors to satisfy final consumption within a chosen sector. Mathematically, the **A** matrix is the product of normalizing the transactions matrix, **Z**, by total industry output, x.
$\mathbf{I}$	Identity matrix
$\mathbf{Z}$	Inter-industry flows between sectors: a set of financial values which describes relationships between all sectors based on their absolute spend on one another
i	(subscript) sector of assessment
ij	(subscript) from sector *i* into sector *j*
n	(subscript) number of input-output sectors
rs	(subscript) from region r to region s
u	Vector of environmental resource intensities (generic). Substituted for w (water), e (energy) and l (land) where appropriate
x	Vector of output
y	Vector of final demand

The basis of an input-output table is a set of linear equations each of which describes the distribution of an industry's product throughout the economy financially (Miller & Blair, 2009). Assume a cross-regional, multi-regional input-output system with n industries where x_i is the total output (production) of a given industry i expressed as a monetary value (e.g. \$1000s), z_i represents inter-industry transactions, and y_i represents the total final demand for industry i's product, globally.

The following accounts for the way in which industry *i* distributes its product through sales to other industries and to final demand:

$$x_i = z_{i1} + \ldots + z_{ij} \ldots + z_{\mathrm{in}} + y_i = \sum_{j=1}^{n} z_{ij} + y_i \tag{2.1}$$

This indicates that output in any given industry *i* is a sum of all intermediate and final demand. Analogous equations can be constructed for each of the *n* industries:

$$\begin{aligned} x_1 &= z_{1l} + \ldots + z_{1j} \ldots + z_{1n} + y_1 \\ &\vdots \\ x_i &= z_{i1} + \ldots + z_{ij} \ldots + z_{\mathrm{in}} + y_i \\ &\vdots \\ x_n &= z_{n1} + \ldots + z_{nj} \ldots + z_{\mathrm{nn}} + y_n \end{aligned} \tag{2.2}$$

Let

$$\mathrm{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \mathbf{Z} = \begin{bmatrix} z_{1l} \cdots z_{1n} \\ \vdots \ddots \vdots \\ z_{nl} \cdots z_{nn} \end{bmatrix}, \mathrm{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} \tag{2.3}$$

Substituting information in 2.2 for 2.3 allows the distribution of each industry's sales to be simplified as:

$$\mathrm{x} = \mathbf{Z}\mathrm{i} + \mathrm{y} \tag{2.4}$$

Where *i* represents a column vector of 1's (of n dimension)

A central principle of IOA is that the output of industries are influenced by the output of other industries which use their output as inputs in their own production processes. For example, the more grain-fed beef that is produced in a year, the more cereal production would be required within the agricultural industry to satisfy this demand (Miller & Blair, 2009). In this case, the ratio of agricultural input to grain-fed beef output, z_{ij}/x_j [the units are (\$/\$)], is denoted by a_{ij}:

$$\mathrm{a}_{ij} = \frac{\mathrm{z}_{ij}}{\mathrm{x}_j} = \frac{\text{Value of cereals bought by the beef sector last year}}{\text{value of cereal production last year}} \tag{2.5}$$

Where z_{ij} is the input from industry i to industry j and x_j is the total input to industry j.

Substituting 2.2 for 2.5 gives:

$$\begin{aligned} x_1 &= a_{al}x_1 + \ldots + a_{1i}x_i \ldots + a_{1n}x_n + y_1 \\ &\vdots \\ x_i &= a_{i1}x_1 + \ldots + a_{ii}x_i \ldots + a_{\mathrm{in}}x_n + y_i \\ &\vdots \\ x_n &= a_{n1}x_1 + \ldots + a_{\mathrm{ni}}x_i \ldots + a_{\mathrm{nn}}x_n + y_n \end{aligned} \tag{2.6}$$

In matrix format:

$$\mathrm{x} = \mathbf{A}\mathrm{x} + \mathrm{y} \tag{2.7}$$

where **A** is the product of normalizing the transactions matrix, **Z**, by total industry output, and is referred to as the *direct requirements matrix*; and, '*y*' is final demand. This can be further manipulated to achieve the form needed for input-output analysis:

$$(\mathbf{I}\text{-}\mathbf{A})\mathrm{x} = \mathrm{y} \tag{2.8}$$

$$x=(\mathbf{I}-\mathbf{A})^{-1}y \tag{2.9}$$

where **I** represents an identity matrix and $(I-A)^{-1}$ denotes the *Leontief inverse matrix*, **L**.

Hence, output can be expressed:

$$x=\mathbf{L}y \tag{2.10}$$

Equation 2.10 forms the basis of IOA. The Leontief demand-pull equation (2.10) can also be expressed in a disaggregated form, by substituting **L** in Equation (2.10) for a series of '**A**' power terms, in order to calculate the output (and associated resource use) required at each production layer of a given supply network. This formulation, termed 'Production Layer Decomposition' is used in Chapter 6 to examine the distribution of water, energy and land across country and sector supply networks.

MRIOA can be undertaken using a complete database of linked national-level input-output tables which capture inter-industry flows within and between national economies; here, consumption can be decomposed into domestic and traded components to evaluate the industry inputs required to satisfy the economic consumption of a single region *r* in relation to territorial and non-territorial production (Peters, 2008):

$$x_r = A_{rr}x_r + y_{rr} + \sum_{s\neq r} A_{rs}x_s + \sum_{s\neq r} y_{rs} \tag{2.11}$$

where x_r is a column vector of output in region *r;* A_{rr} is the direct requirements matrix of region *r;* y_{rr} is the final demand for locally produced commodities and services in region *r*. A_{rs} and y_{rs} are analogous to A_{rr} and y_{rr} respectively, but refer to cross-regional relationships. It is worth noting this equation 2.11 can be manipulated to make x_i the subject of assessment to evaluate production dependencies from the perspective of a single sector.

By adding environmental information within this framework which aligns with the input-output industries defined, an environmental burden (or footprint) can be assigned to the financial transactions associated with domestic consumption (Tukker & Dietzenbacher, 2013).

The consumption-based environmental footprint of a region u_r is calculated by pre-multiplying the Leontief inverse, derived on page 40, by a row vector of direct environmental intensity coefficients u for each sector within each region and post-multiplying by final demand within the specified region:

$$u_r = u.x_r \tag{2.12}$$

Specific environmental footprints for nexus-based assessment can be obtained by substituting u in equation 2.12 with water *(w)*, energy *(e)* and land *(l)* vectors:

$$w_r = w.x_r \tag{2.13}$$

$$e_r = e.x_r \tag{2.14}$$

$$l_r = l.x_r \tag{2.15}$$

MRIOA relies on the integration of a vast inventory of socio-economic and environmental data. The next section outlines the datasets that have been used and how data was managed the research for this thesis.

Several criteria were used to select appropriate data sources for the development of a framework for flexible nexus-based assessment. First, where possible open-access data was used rather than proprietary data, to support the required transparency of method development and reproducibility of analysis. Second, data was to be sourced from reputable sources and feature in peer-review studies. Third, datasets were chosen that demonstrated regular cycles of release to ensure that the methodological framework developed in this thesis is ‘time-proofed’ for future use.

Table 2.3 MRIO databases

MRIO and author	Temporal coverage	Spatial coverage	Sectoral coverage	Status	Availability
Eora (Lenzen et al., 2013b)	1990-2015	189 countries	14,838 sectors	Continually updated	Free
Exiobase (Stadler et al., 2018)	1995 – 2011	44 countries 5 rest of world regions	163 industries 200 products	Released in 2012 Last updated 2018 Update status unknown	Free
GTAP (Peters et al., 2011)	1990; 1992; 1995; 1997; 2001; 2004; 2007; 2011; 2014	121 countries 20 aggregate regions	65 sectors	Release in 1990 Updated every 3-4 years Last updated 2019	Pay-walled
OECD ICIO (Wiebe & Yamono, 2016)	2005-2015	OECD 1 rest of world region	Variable	Released in 2012 Last updated 2018	Free
WIOD (Dietzenbacher et al., 2013a)	2000-2014	43 countries 1 rest of world region	56 sectors	Release in 2012 Update status unknown	Free

2.2.6 Consumption, production, and trade data

Monetary and physical production, consumption, and trade accounts form the basis of analysis within this research. Table 2.3 summaries the main global MRIO databases for undertaking environmentally-extended MRIOA.

Of the global MRIO databases available, the Eora (2019) database, developed by Lenzen et al. (2012a), was chosen to be used within this proposed thesis research. This MRIO database was selected due to its superior time series, country-level coverage, and sectoral resolution (Lenzen et al., 2013b). The Eora (2019) database combines economic and environmental accounts for 189 countries between 1990-2015 at their full sectoral resolution, covering a total of 14838 sectors, as illustrated in Figure 2.4.

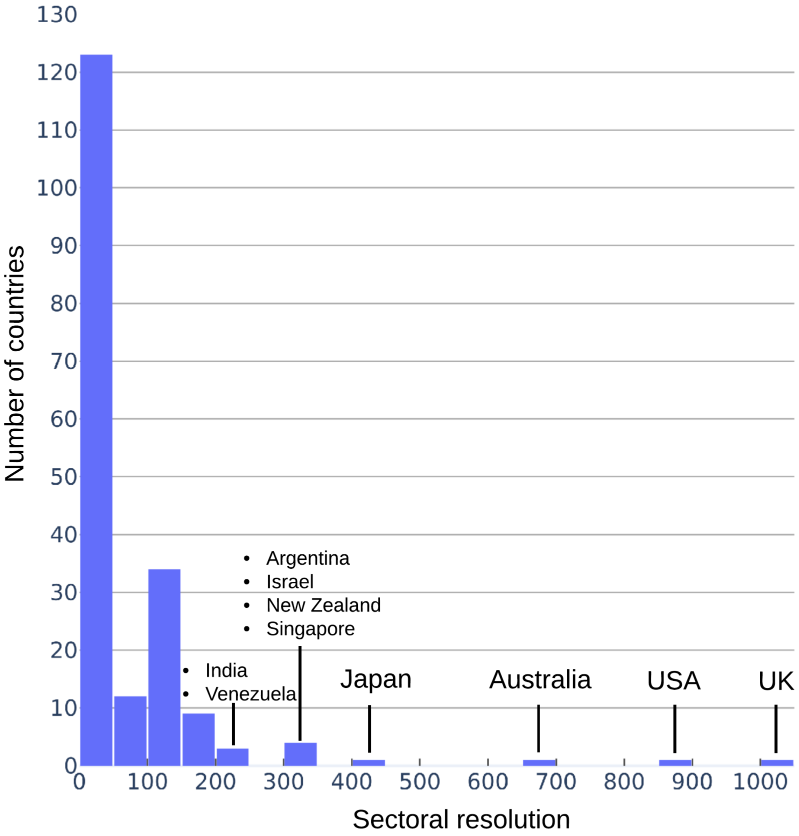

Fig. 2.4 Sectoral resolution of the Eora MRIO database

A distinct benefit of Eora is that it distinguishes individual developing countries which are often aggregated into ‘Rest of World’ regions in other MRIO databases; this is advantageous since resource-related pressures from global consumption are often concentrated in developing countries (*cf* Chapagain & Hoekstra, 2008; Dalin et al., 2017; Flach et al., 2016; MacDonald et al., 2015; Tuninetti et al., 2019). The basic components of MRIOA are summarised in Figure 2.5. Appendix A illustrates how these were calculated computationally.

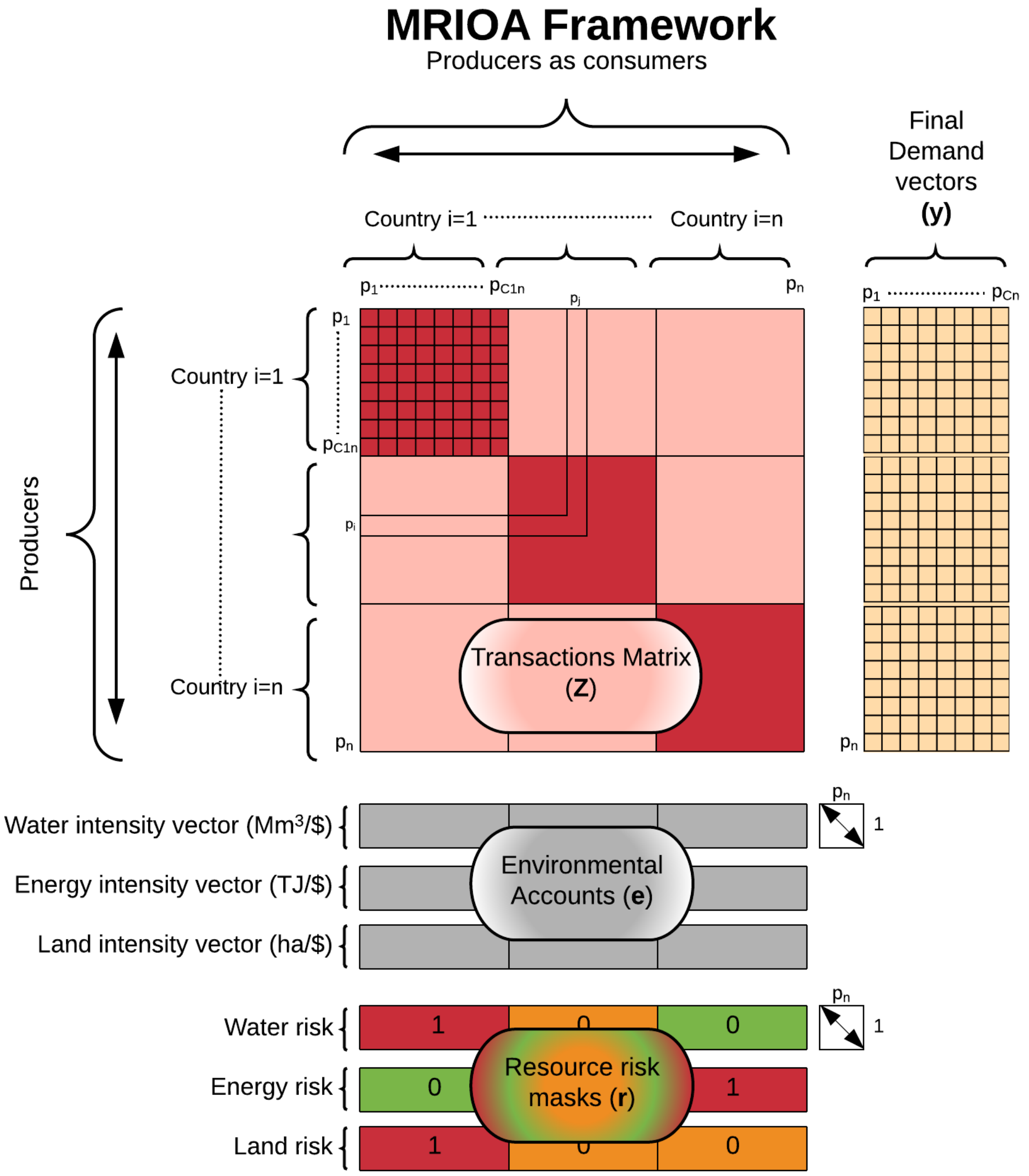

Fig. 2.5 Components of MRIOA for assessment of the global WEL system

Although MRIO databases all follow the same basic approach to consumption-based accounting – the Leontief demand-pull model described in section 2.2.5 – different assumptions and data processing methods result in discrepancies in the environmental consumption footprints calculated between systems (*cf* Arto et al., 2014; Inomata & Owen, 2014; Moran & Wood, 2014; Owen et al., 2014). However, analysis by Moran & Wood (2014) found that environmental footprints generated from different MRIO databases are converging, highlighting their increasing reliability in recent years. Moreover, the top-down modelling approach followed by MRIOs also enables flexible quantitative integration of additional data from sub-national input-output tables, which are becoming increasingly available, especially for major production centres such as the US (Wiebe & Yamono, 2016), China (Dong et al., 2014; Guan & Hubacek, 2007; Jiang et al., 2015), and Indonesia (Faturay et al., 2017). At the time of writing, the Eora (2019) database was the most detailed MRIO database available.

2.2.7 Data Visualisation

A large selection of different data visualisation formats are used throughout this thesis, although three formats are particularly favoured. First, global choropleth maps are used to compare the source and severity of national footprints. These enable straightforward country profiling and comparison and interpretation of features in global regions. Second, box plots are used frequently to compare, in relative terms, spatial, sectoral and supply chain sources of national resource footprints. Box plots also expose mean and median values within specific analysis which are instructive for high-level assessment. Third, polar plots are used to condense large amounts of information (e.g. non-domestic resource use across thousands of sectors) into simple figures which convey general trends of importance. Other potential data visualisation approaches are discussed in Section 7.4.4. Where appropriate, raw values are also used to convey accurately noteworthy findings related to human influence across the WEL system, from global, country and sector perspectives. Data linked to the empirical analysis within this assessment are available at Taherzadeh (2020).

2.2.8 Computational requirements

Modelling country and sector influence across the global WEL system using MRIOA is both computationally complex and computationally demanding. Several aspects of the analysis within this thesis are computationally particularly complex. First, the Eora (2019) database used is the only MRIO database which combines national input-output tables of different sectoral resolutions. This acts to preserve national economic and environmental account with the highest level of detail. However, the calculation and interpretation of resource footprints for countries and sectors involves manipulation of, and looping across, matrices of uneven size. Such procedures requires additional programming code, which is detailed in Appendix A, and available from Taherzadeh (2020). This partly explains why several users of the Eora (2019) database prefer to work with its harmonised, 26-sector resolution version. Second, to understand the spatial, sectoral and supply scope of national resource footprints they must be calculated and analysed in a disaggregated way. Within this thesis, the full resolution version of the Eora (2019) database is used, at 189 country and at full sectoral resolution (see Figure 2.4). This brings a rich level of detail, as demonstrated in Chapters 4, 5 and 6, in terms of how the resource footprint of countries and sectors are imposed across the world economy. However, such insights require significant additional work to distill the output data when compared to conventional resource footprint analysis which aggregates country-sector interdependencies into a single value. Third, the multi-dimensional nature of analysis in this thesis involves country and sector resource footprint assessment in relation to multiple environment indicators and risk categories, across different scales and system boundaries. This demands the integration of disparate forms of data, re-organisation of the Eora (2019) database (e.g. for analysis of global regions) and diagnostic checks to ensure resource flows balanced between analyses. The challenge of such data manipulation and processing is compounded by the sheer computational demands of analysis within this thesis.

The high computational demands of analysis within this thesis are symptomatic of the macro-economic and multi-dimensional nature of the research questions examined. Figure 2.6 summarises the scope of analysis in Chapters 4, 5 and 6 in terms of data points and computer memory requirements. In total, it is estimated that analysis in this thesis generates approximately 359 billion data points, arising from the 10-layer Production Layer Decomposition of water, energy and land use across country and sector supply networks in Chapter 6. This corresponds to 287.48TB, based on 8 bytes per value. A similarly demanding analysis was required for analysis in Chapters 4 and 5. Due to these computation demands, a supercomputer was used for all primary analysis in Chapters 4, 5 and 6. Analysis was typically run as a batch submission of many runs on a 32 core node consisting of 192GB of memory each of which lasted approximately 2 hours. Slurm (Simple Linux Utility for Resource Management) was used to schedule jobs on the supercomputer. Data outputs from these jobs were transferred via Secure Shell Protocol (SSH) from a local high-performance Linux-based machine for further analysis. Analysis was performed in MATLAB^{TM} on both the supercomputer and local machine. Invariably, programming code could not be fully tested on the local machine and had to be debugged based on error messages and outputs arising from supercomputer runs. The lack of a virtual environment for full code development made the early development of the MRIOA model used in this thesis particularly challenging. The scope of analysis within this thesis reflects the time cost of such process.

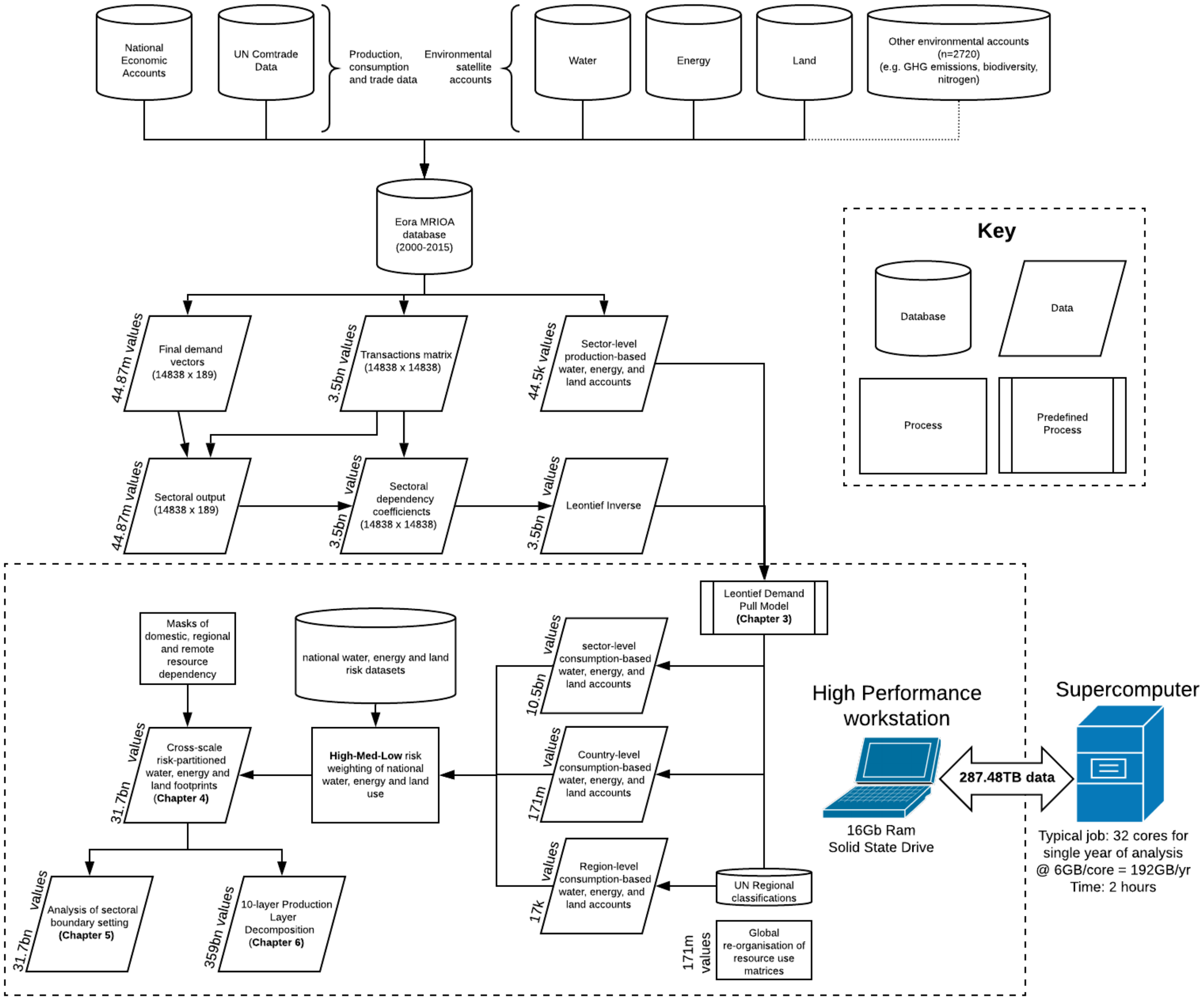

Fig. 2.6 Computational requirements of analysis

Chapter 3

The water-land nexus of international soybean trade

Yet while the EU's complicity in importing soy from South America that's causing environmental destruction is clear, unravelling the supply chains - and linking specific on the ground abuses to the EU market and the major agribusinesses who supply it with soy - is far more difficult.

Polsterer, 2018

3.1 Introduction

This thesis attempts to understand human influence across the WEL system within the context of globalised, cross-sectoral, and complex consumption and production systems. The previous chapter (2) highlighted the potential application of Material Flow Analysis (MFA) and Multi-Regional Input-Output Analysis (MRIOA) to this end. This chapter attempts to examine the contribution of international trade to pressures across the WEL system using MFA and associated physical environmental and commodity accounts. The purpose of this chapter is two-fold; (i) to test MFA within the research context of this thesis and (ii) to develop a case study which addresses the limited study of trade-related resource use within nexus scholarship. MFA was chosen over MRIOA for this initial study for several reasons. First, this thesis research was guided by earlier work at the University of Cambridge (*cf* Allwood et al., 2011; Bajželj et al., 2013, 2014; Cullen & Allwood, 2010; Konadu et al., 2015b; Mukuve & Fenner, 2015b; Qin et al., 2015), in the development of the Foreseer Tool (University of Cambridge, 2013), reviewed in Chapter 2, which uses MFA to assess pathways of human influence on the WEL system. Second, given the relative strengths and limitations of MRIOA and MFA - discussed in Section 2.2.2 and elsewhere (*cf* Hubacek & Feng, 2016; Schaffartzik et al., 2015; Weisz & Duchin, 2006) - the latter method offers potentially more suitable data for the development of a single nexus assessment case study. Third, this study was conceived in the early stage of research for this thesis, with Dr Dario Caro (Aarhus University), following the 20th General Assembly of the European Geophysical Union in 2018, where the broader objectives of the thesis research were presented (Taherzadeh, 2018).

The agri-food system serves as the focal point of this case study testing the application of MFA to global nexus assessment. Demand for agricultural output links countries, sectors, and consumers in international supply chains (Shutters & Muneepeerakul, 2012). In recent years, trade in agricultural commodities has increased dramatically to satisfy rising demand for food, animal feed, and biofuels (FAO, 2011; Lambin & Meyfroidt, 2011; Porkka et al., 2013). These transboundary dependencies have become an increasingly important driver of groundwater depletion (Dalin et al., 2017; Konar et al., 2011; Wang & Zimmerman, 2016), land use and deforestation (Beckman et al., 2017; Henders et al., 2015), and greenhouse gas emissions (Dalin & Rodríguez-Iturbe, 2016) in agricultural systems. Consequently, analysis of trade flows offers an increasingly important pathway of human influence across the WEL system.

A growing literature has sought to establish trade-environment linkages to identify critical actors, activities, and actions to improve sustainability and accountability across agricultural supply chains. This body of evidence suggests: (i) decisions concerning agricultural production are driven by international markets (Beghin et al., 2017; Headey, 2011; Hertel et al., 2014; MacDonald et al., 2015); (ii) this influence accounts for a large proportion of the environmental impacts embodied in agricultural supply chains (Breu et al., 2016; Dalin & Rodríguez-Iturbe, 2016; Wiedmann & Lenzen, 2018); and (iii) trade decisions are an important, but underexplored, area in the management of these impacts (Himics et al., 2018; Islam et al., 2016; Tamea et al., 2016). Such issues have also gained increased traction in government and industry where policy makers become increasingly concerned about the risks they face and drive in relation to agricultural trade (Green et al., 2016; Pretty et al., 2010; Sutherland et al., 2012). Still, there is a widening gap between the understanding of trade-related environmental impacts and the evidence base needed to manage them (Wiedmann & Lenzen, 2018). Effective policy levers remain hidden within the complexity of globalised agricultural supply chains. Mapping resource flows across agricultural trade networks renders this problem space more visible and in turn, more manageable.

Soybean production is a major source of natural resource use within the agricultural sector. Trade of soybean corresponds to large quantities of water, land, and related CO_2 emissions, that are often driven by consumption of soybean products in remote countries and regions (Arima et al., 2011; Dalin & Rodríguez-Iturbe, 2016; Henders et al., 2015; Karstensen et al., 2013; Schmitz et al., 2012). These pressures are projected to increase in the future against the backdrop of growing demand for animal feed and biofuels (Karstensen et al., 2013; Lapola et al., 2010). Although the environmental impacts of soybean trade have received significant attention in recent years, studies are limited on two fronts. First, they tend to evaluate the burden of soybean trade against a single environmental dimension - water, energy, or land. Whilst instructive, such unitary assessments do not reveal potential trade-offs and synergies arising from management of individual resource impacts driven by agriculture and soybean trade across multiple environmental systems (Leck et al., 2015). This integrated view of resource use has become increasingly important due to the multiple pathways which link the exploitation of natural resources in supply chains (Taherzadeh et al., 2018). Second, environmental assessments of soybean trade often provide limited information on the underlying sectoral drivers and consumption patterns responsible. Since soybeans are consumed across multiple sectors - e.g. food, fodder and fuel (WWF, 2014) -

such an assessment is critical to identify appropriate policies to moderate demand for soybean and its associated environmental impacts. Within the context of this thesis research, soybean is uniquely suited to the research scope of this thesis, due to the globalised, cross-sectoral, and complex nature of its supply chain.

In this study, the water use and land area associated with soybean trade (hereafter, 'Virtual Water Trade', VWT, and 'Virtual Land Trade', VLT) is estimated and the sectors responsible are identified following a Physical Trade Analysis (PTA) approach, using physical environmental and commodity accounts, and based on the principles of MFA. This analysis combines physical import and export data and associated resource use information from 166 countries during the period 2000–2016. Section 3.2 describes the data and methods used in this analysis. Section 3.3 presents the findings of this analysis within the context of country (Section 3.3.1) and sectoral (Section 3.3.2) responsibility for water and land use embodied in soybean trade. Section 3.4 reflects on (i) how this analysis can guide sustainable production, consumption, and trade decisions, (ii) the limitations of the study, and (iii) the avenues for future research. Lastly, Section 3.5 outlines the implications of this study for the wider assessment of human influence across the WEL system, as outlined in Chapter 1.

3.2 Methods

Trading patterns between countries redistribute the environmental burdens of production and consumption. Several modelling approaches have emerged in response to the need for better understanding of how countries impose resource demands beyond their territories via international trade in resource-intensive commodities. These approaches fall into two main categories: Physical Trade Analysis (PTA) and Multi-regional Input Output Analysis (MRIOA). PTA, a form of MFA, accounts for the physical volume of commodity production (in tonnes), and the associated resource use embodied in international trade (Fischer-Kowalski et al., 2011). MRIOA evaluates how the demand of a sector or country is distributed throughout the world economy based on financial transactions between sectors and enumerates the production and associated resource requirements arising from these estimated dependencies (Kitzes, 2013). Although these methods both apply sectoral dependency coefficients to sectoral outputs and inputs across the economy - PTA using physical data and MRIOA using financial data - each offers a different vantage point of trade-related resource use. PTA lends itself to the analysis of accurate, commodity-level resource trade due to superior sectoral resolution and more precise resource flow accounting using physical environmental and commodity accounts (Galli et al., 2012; Rodrigues et al., 2018; Tukker et al., 2018). Meanwhile, IOA analysis enables a more comprehensive coverage of resource demand embodied in international supply chains at a sector-wide or economy-wide scale (Kitzes, 2013). In this study, a PTA approach is used to evaluate commodity-level virtual water and land trade arising from international soybean trade. For completeness, an analysis of the consumption drivers of soybean production, trade and corresponding water and land impacts is presented in Section 3.3.2. This section begins by outlining the data uses within this study (Section 3.2.1), then introduces the methodological procedures for calculating water use associated with soybean trade (Sections 3.2.2 and 3.2.3) and land are associated with soybean trade (Section 3.2.5).

3.2.1 Data requirements

Data concerning the quantity of soybean traded from 2000 to 2016 were provided by UN Comtrade (2018). A detailed trade matrix representing the import and export of soybean amongst 166 countries, detailed in Taherzadeh (2020), was compiled and analysed for each year. The quantity of soybean used in the paper captured “soybeans whether or not broken” under the Harmonized System classification of products (HS=1201). To calculate the soybean water demand specific parameters relating to the estimation of the soybean evapotranspiration were obtained from Allen et al. (1998) and annual soybean yields for each country were provided by FAO (2019). The annual soybean area harvested as well as the annual production of soybean for each country were also provided by FAO (2019). More detailed information about specific parameters used in this assessment of water and land use embodied in soybean trade are provided in the ensuing sections.

3.2.2 Estimation of virtual water flows

This analysis focuses on the “green” component of the water footprint and associated virtual water trade related to international soybean trade. The green soybean water use represents the total rainwater evaporated from the field during the growing period (Naranjo-Merino et al., 2018). Green water is soil moisture, which is drawn from the soil by plants and transpired, and replenished by rainfall (Hoekstra et al., 2011). According to Mekonnen & Hoekstra (2011), the green water footprint of soybean accounts for around 95% of its total water footprint globally. Additional information about the blue and grey water footprint of international soybean trade are provided for completeness in Taherzadeh (2020), using global average estimates in Mekonnen & Hoekstra (2011).

3.2.3 Soybean specific water demand

For country *n* specific water demand (expressed as m^3 of water per tonne of soybean) is based on FAO data on soybean water requirement (SWR) and soybean yield (SY) as follows:

$$SWD_n = SWR_n/SY_n \tag{3.1}$$

where SWD_n indicates the specific water demand of soybean in country *n*, SWR_n soybean water requirement (m^3 ha^{-1}) in country *n* and SY_n the soybean yield (tonne ha^{-1}) in country *n*.

SWR was estimated as soybean evapotranspiration, by following the guidelines for computing crop water requirements developed by Allen et al. (1998) whereas SY (expressed as tonne ha^{-1}) was derived from the FAOSTAT database for each country (FAO, 2019)

SWR is estimated from the accumulated soybean evapotranspiration ETs (mm day^{-1}) over the complete growing period. ETs (expressed as mm day^{-1}) is obtained by multiplying the reference soybean evapotranspiration (ET_o) by the soybean coefficient K_s:

$$ET_s = ET_o.K_s \tag{3.2}$$

ET_o (mm day^{-1}) is calculated by the FAO Penman-Monteith equation according to Allen et al. (1998) and captures climatic parameters such as the mean annual temperature in the country and the typical weather regimes of the country throughout the year. The mean annual temperature in each nation was provided by NOAA (2018). Climate regimes were based on data reported by CIA (2017). K_s, represents the soy-related water stress coefficient, based on Allen et al. (1998). Estimation of virtual water trade of soybean (VWT) refers to the soybean-specific water use corresponding to the physical quantity of soybean produced for export. For country *n* the VWT is obtained by multiplying the quantity of soybean traded (ST) by the soybean-specific water demand (SWD) as follows:

$$VWT_{ne_t,ni_t} = ST_{ne_t,ni_t,}.SWD_{ne_t} \tag{3.3}$$

VWT indicates the virtual water trade (m^3 yr^{-1}) from exporting country ne to importing country n$_i$ in year $_t$. The soybean traded (ST) represents the quantity of soybean traded from exporting country n$_e$ to an importing country n$_i$ in year *t* and is provided by UN Comtrade (2018).

Equation 3.3 assumes that if soybean is exported from a certain country it is actually grown in this country and not in another country from which the soybean was imported for further export. Although export and re-export flows are formally classified in Comtrade (2018), this does not enable traceability of soybeans embodied in secondary products which are subsequently exported (e.g. tofu, beef or pet food).

The gross virtual water import (GVWI) to a country n$_i$ is the sum of its virtual water imports whereas the gross virtual water export (GVWE) from a country n$_e$ is the sum its virtual water export:

$$GVWI_{n_t} = \sum_{n=1}^{n=166} VWT_{ni_t} \tag{3.4}$$

$$GVWE_{n_t} = \sum_{n=1}^{n=166} VWT_{ne_t} \tag{3.5}$$

It follows that the net virtual water import of country n is equal to the gross virtual import minus the gross virtual water export:

$$NVWI_{n_t} = GVWI_{n_t} - GVWE_{n_t} \tag{3.6}$$

When *NVWI* is positive it means that country *n* is a “net virtual water importer”; where *NVWI* is negative, a country is a “net virtual water exporter”.

3.2.4 Estimation of water dependency and water self-sufficiency

Water dependency (WD) is a national indicator reflecting the level to which a country relies on non-territorial water resources. It is a percent value estimated as the ratio between the *NVWI* and the total national water appropriation:

$$WD = NVWI/\{WU + NVWI\} \tag{3.7}$$

Where WU is the total water use in the country for growing soybean. Equation 3.7 holds when $NVWI \geq 0$. When NVWI is <0, the country is a net virtual water exporter. Equation 3.7 only holds when WD >0.

$$WSS = WU/\{WU + NVWI\} \tag{3.8}$$

The water self-sufficiency of soybean (WSS) indicates the extent to which country n supplies the water needed to satisfy its domestic demand for soybean. WSS is a percentage estimated as the ratio between WU and the total water use associated with soybean consumption in a nation (WU + NVWI)

The WSS of country n is calculated using the WD of a country as in Equation 3.7:

$$WSS = 1 - WD \tag{3.9}$$

3.2.5 Estimation of virtual land flows

Assessments of water use embodied in international trade predate studies of land use embodied in international trade. However, the latter is becoming increasingly common due to the closely coupled dependency between water and land use embodied in agricultural commodity trade. To enable cross-comparison with soybean-related virtual water trade this analysis provides equivalent calculations of soybean-related virtual land trade and its sectoral drivers.

Virtual land trade of soybean (VLT) refers to the soybean-specific land use corresponding to the physical quantity of soybean produced for export. Raw commodity and export data for soybean were obtained from UN Comtrade (2018). For country n its VLT is obtained by multiplying the quantity of soybean traded (ST) by a soybean-specific land intensity (LI) which is estimated as the ratio between the national soybean-specific area harvested (ha) and the national soybean-specific production (tonnes), in the year t:

$$VLT_{ne_t,ni_t} = ST_{ne_t,ni_t}.LI_{ne_t} \tag{3.10}$$

Enumerating the total VLT flows across all 166 trading partners produces an estimate of the Gross Virtual Land Import (GVLI) and Gross Virtual Land Export (GVLE) for a given country, n:

$$GVLI_{ni_t} = \sum_{ne} VLT_{ne_t,ni_t} \tag{3.11}$$

$$GVLE_{ne,t} = \sum_{ni} VLT_{ne_t,ni_t} \tag{3.12}$$

The net virtual land import of country n is equal to the GVLI minus the GVLE:

$$NVLI_{n,t} = GVLI_{n_t} - GVLE_{n_t} \tag{3.13}$$

When NVLI is positive it means that country *n* is a "net virtual land importer"; where NVLI is negative, a country is a "net virtual land exporter".

3.3 Analysis

This section begins by exploring the major countries responsible for soybean export and import, the related water use and land area embodied in these flows, and how this has evolved over time (Section 3.3.1). Section 3.3.2 examines the sectoral drivers of this system from the perspective of importing regions.

3.3.1 Country responsibility for soybean production

In 2016, global green water used for producing soybean was 2389Gm^3 whereas the green water embodied in international trade of soybean was 812Gm^3. In the same year 121Mha of land was used for producing soybean globally and the land embodied in international trade of soybean was 42Mha, equivalent to the total land area of Paraguay (40.68Mha) and larger than the land area in 177 other countries (FAO, 2019). These findings imply that around one-third (34%) of soybean-related green water use and soybean related land use is driven by international trade, and not by domestic production for domestic consumption. Overall, virtual water trade of soybean increased by 298% during the period 2000–2016 with an average growth per year of about 9% whereas the virtual land trade increased by 118% with an average growth per year of about 5% (Figure 3.1-b). In contrast to the moderate growth of virtual land trade from soybean export, a substantial growth of the virtual water trade of soybean starting from 2010 is observable (Figure 3.1-a).

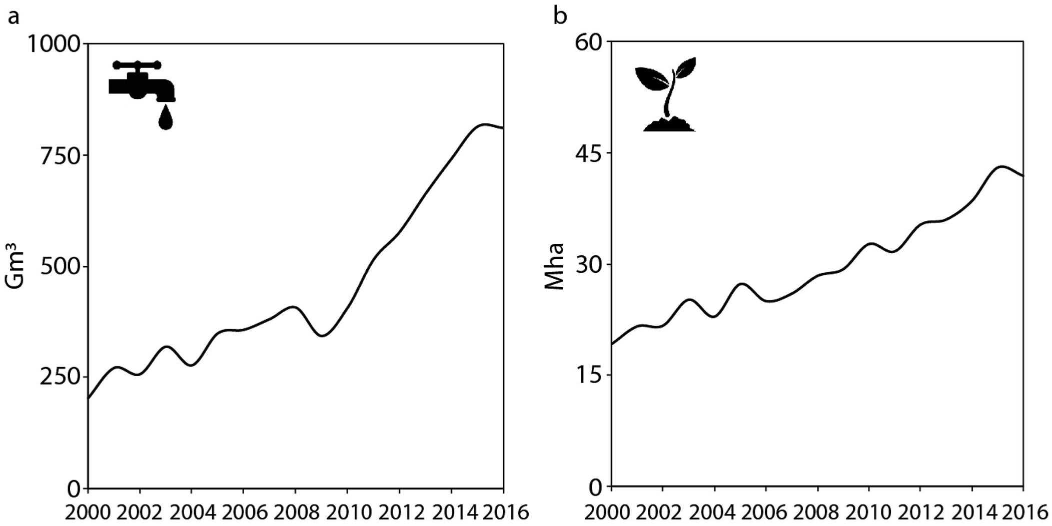

Fig. 3.1 Global virtual water and land trade associated with soybean production
Trend in global virtual water trade (a) and virtual land trade (b) of soybean during the period 2000–2016.

The USA is the largest gross exporter of soybean-related virtual water. In 2016, the USA ‘exported’ 390Gm^3 of water embodied in its production of soybean (Figure 3.2-a). Moreover, in the period analysed (2000–2016) soybean-related gross virtual water export in the USA increased by 540% (Figure 3.2-a) with a growth rate of about 12% per year. Brazil and Argentina are also significant soybean-related gross virtual water exporters, exporting 275Gm^3 and 74Gm^3 respectively in 2016 (Figure 3.2-a). While the increase in gross virtual water export in Argentina was moderate (+60% from 2000 to 2016), Brazil exhibited substantial growth (+262% from 2000 to 2016, Figure 3.2-a). The greatest soybean-related national water appropriation (WU + NVWI) was found in China (Table 3.1) due to its high net virtual water import. However, Table 3.1 shows that the Chinese utilisation of domestic water (WU) for growing soybean (41Gm^3) was low when compared with the USA (850Gm^3), Brazil (534Gm^3) and Argentina (427Gm^3). Consequently, China was the largest soybean-related net virtual water importer in 2016 (534Gm^3 of water imported, Figure 3.3-a). From 2000 to 2016 soybean-related gross virtual water import in China increased by 854% with just 56Gm^3 of gross virtual water imported in 2000 (Figure 3.2-b). Such an increase corresponds to about 15% growth per year. This step-wise change in China's soybean-related imports and associated virtual water and land use (Figure 3.2) reflects the country's curtailing production of soybean due to (i) overexploitation of groundwater in Northern China where soybean is primarily grown, (ii) changing agricultural production to higher value crops, and (iii) conversion of land to residential and industrial use (Brown-Lima et al., 2010). The Netherlands and Mexico were the second largest soybean-related gross virtual water importers (about 29Gm^3) in 2016 (Figure 3.2-b) with an increase of 21% and 180%, respectively over the years analysed.

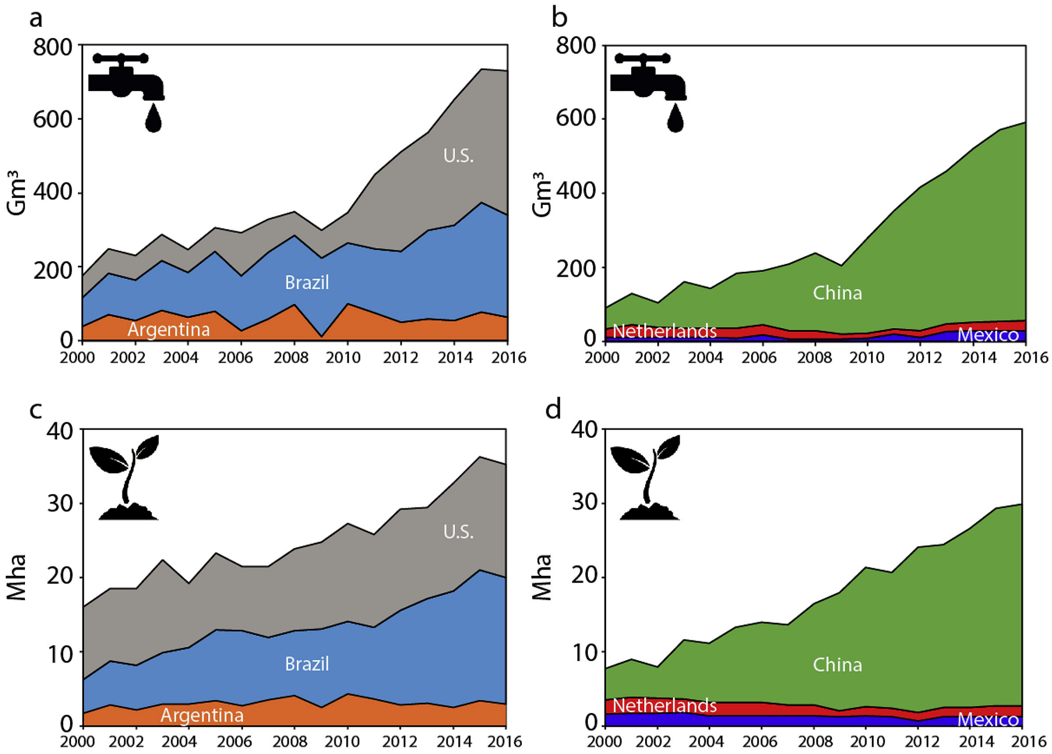

Fig. 3.2 Countries responsible for water and land use embodied in soybean trade

Trend in water (a,b) and land (c,d) embodied in soybean trade for the largest three exporting (a, c) and importing (b, d) countries during the period 2000–2016.

Brazil is the largest gross virtual exporter of soybean-related land use. In 2016, Brazilian soybean exports corresponded to around 17Mha of land (Figure 3.3-b). Moreover, in the period analysed (2000–2016) soybean-related gross virtual land export in Brazil increased by 280% (Figure 3.2c) with a growth rate of about 9% per year. In 2000 the USA was the largest gross exporter of land for soybean production (9.8Mha), but the increase of land virtually exported from the USA over the period analysed (56%; 2.8% per year) was significantly lower than that for Brazil (Figure 3.2c). Argentina is also a significant soybean-related gross virtual land exporter, exporting about 3Mha in 2016 (Figure 3.3-b). However, from 2000 to 2016 the increase in gross virtual land export in Argentina was moderate (+71%). China was the largest soybean-related net virtual land importer in 2016 (27 Mha of land imported, Figure 3.3-b). From 2000 to 2016 soybean-related gross virtual land import in China increased by 548% (Figure 3.2d) - an increase of about 12% growth per year. The Netherlands and Mexico were the second largest soybean-related gross virtual land importers (1.5 and 1.2Mha respectively) in 2016 (Figure 3.2d).

Figure 3.4-a shows that the dominant global fluxes of gross virtual water linked to soybean trade in their export from the USA and Brazil to China (248Gm^3 and 212Gm^3, respectively). The flows from Argentina to China, the USA to Mexico, and Uruguay to China are also substantial (58Gm^3, 26Gm^3, and 12Gm^3 respectively). The soybean-related gross virtual water exports from the USA and Brazil to Europe are less significant (Figure 3.4): the Netherlands and Germany were the largest European importers from the USA (15Gm^3 and 11Gm^3 of water imported, respectively) whereas Spain was the largest importer from Brazil (10Gm^3). Other moderate flows resulted from soybean trade from the USA to Japan (16Gm^3) and from Brazil to Thailand (11Gm^3).

The largest global fluxes of gross virtual land relate to soybean exports from Brazil to the USA and China (13 and 10Mha, respectively). The flows from Argentina to China and from the USA to Mexico are also significant (2.7 and 1Mha, respectively). Other moderate flows resulted from soybean trade from Uruguay to China and Brazil to Thailand (both 0.7Mha), and from the USA to Indonesia (0.6Mha). As might be expected from the above, the soybean-related gross virtual water exports from the USA and Brazil to Europe is less significant. Within this context, the Netherlands and Spain were the largest European importers from the USA (0.6Mha of land imported). A similar flux (0.6Mha) was found between export from the USA to Japan.

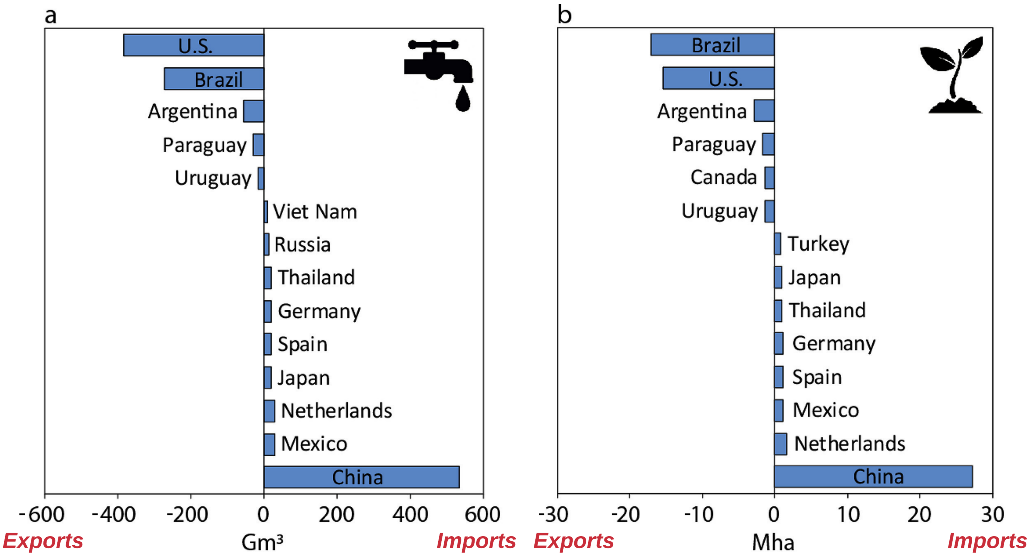

Fig. 3.3 Net virtual water and land trade associated with soybean production

The largest net virtual water (a) and land (b) exporters (left side) and importers (right side) for international soybean trade in 2016.

Table 3.1 Water and land intensities associated with soybean production and trade

Water and land intensities (SWD and LI, respectively) associated with the largest five exporting countries in 2000 and 2016. Percentage variation of water and land intensities during the period 2000–2016 is also shown as well as the their relative efficiencies in 2000 and 2016. The change in efficiency of water and land use calculated as the difference between the water/land content in 2016 (tonne 2016×water/land intensity 2016) and the water/land content in 2016 with the intensity of 2000 (ton 2016×water/land intensity 2000) and expressed in terms of avoided resource use. It represents the water and land saved or further exploited on the basis of an increase or a decrease of resource efficiency between 2000 and 2016. When this change in efficiency is negative it means that in 2016 a higher amount of water (or land) has been exploited with respect to the efficiency levels of 2000 (the intensity increased between 2000 and 2016). When the change is resource efficiency is positive it means that in 2016 a lower amount of water (or land) has been exploited with respect to the efficiency levels of 2000 (the intensity decreased between 2000 and 2016).

Indicator	**Units**	**US**	**Brazil**	**Argentina**	**Paraguay**	**Uruguay**
Water intensity (SWD) 2000	m^3/t of soybean	2458	6986	9903	6628	8652
Water intensity (SWD) 2016	m^3/t of soybean	7251	5544	7270	6711	7204
Change in water use efficiency	%	-195	21	27	-1	17
Land intensity 2000	ha/t of soybean	0.39	0.42	0.43	0.39	1.31
Land intensity 2016	ha/t of soybean	0.29	0.34	0.33	0.37	0.52
Change in land use intensity	%	27	17	23	7	61
Avoided water use (2000–2016)	Gm^3	-258.4	71.7	23.2	-0.4	3.8
Avoided land use (2000–2016)	Mha	5.6	3.6	0.9	0.1	2.1

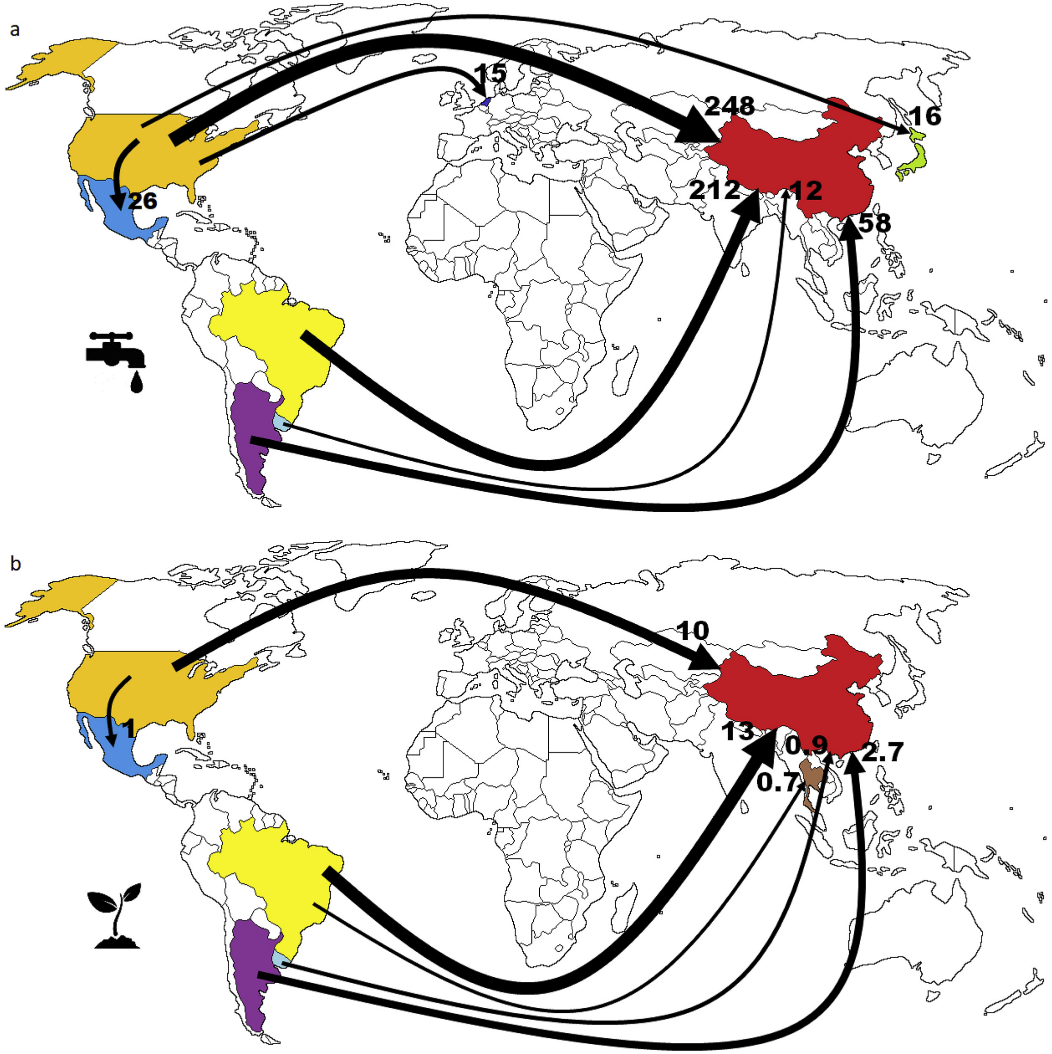

Fig. 3.4 Major fluxes of virtual water and land use embodied in soybean trade

Largest transboundary fluxes of virtual water (a) and land (b) trade associated with global soybean trade between major importers and exporters in 2016. Map shows fluxes of virtual water greater than 10Gm^3 *fluxes of virtual land greater than 0.6Mha.*

Table 3.2 Water self-sufficiency of soybean importers and exporters

Gross virtual water export (GVWE, see equation 3.5), the gross virtual water import (GVWI, see equation 3.4), the net virtual water import (NVWI), the water used (WU), the national water appropriation (WU + NVWI), the water dependency (WD, see equation 3.7) and the water self-sufficiency (WSS, see equation 3.8) for the largest importing/exporting countries in the world.

	GWE (Gm^3)	**GWI (Gm^3)**	**NWI (Gm^3)**	**WU (Gm^3)**	**WU + NWI (Gm^3)**	**WD (%)**	**WSS (%)**
Argentina	63.9	5.8	-58.2	427.5	369.3	0	100
Brazil	275.5	2.6	-272.9	533.9	260.9	0	100
China	0.5	534.9	534.4	41.6	576	93	7
Germany	0.1	19.5	19.3	0.1	19.4	99	1
Japan	0	20	20	0.9	20.9	96	4
Mexico	0	28.9	28.9	7.8	36.7	79	21
Netherlands	1.2	29	27.8	0	27.8	100	0
Paraguay	31.1	0	-31.1	61.5	30.4	0	100
Russian	2.2	14	11.8	15.2	27	44	56
Spain	0.3	19.6	19.4	0	19.4	100	0
Thailand	0.1	17.8	17.7	0.4	18.1	98	2
Uruguay	19.1	0.2	-18.9	15.9	-3.0	0	100
US	390.9	5.4	-385.5	849.9	464.4	0	100
Viet Nam	0	10.3	10.3	1.9	12.1	85	15

Table 3.2 shows WSS and WD values for the largest gross virtual water exporting and importing countries respectively. Concerning WD, a value of zero means that gross virtual water imports and exports are in balance or that there is net virtual water export; this characterises countries such as the US, Brazil Argentina, Paraguay and Uruguay (Table 3.2). Instead, WSS, which is the counterpart of WD, denotes the capability of supplying the water needed for production of domestic demand for soybean in a country. WSS is low when a country is heavily reliant on virtual water imports; this characterises China, Spain, the Netherlands, Thailand and Germany (Table 3.2).

Virtual water trade flows from highly stressed to low stressed countries are also examined to contextualise this analysis. Estimates of country-level water stress are provided by the World Resource Institute's Aqueduct Projected Water Stress Country Rankings (WRI, 2015) which are summarised in Taherzadeh (2020). When viewed within the context of these data, low-water-stressed countries were net exporters of soybean-related virtual water. Furthermore, in 2016, low-water-stressed countries exported 298Gm^3 of soybean-related virtual water to highly stressed countries, whereas highly stressed countries exported 61Gm^3 of soybean-related virtual water to low stressed countries.

3.3.2 Sectoral drivers of soybean production

Although instructive, country-level analysis of soybean trade conceals the underlying drivers of soybean demand. Sectoral analysis of soybean demand is necessary to establish a link between consumption activities, soybean production and its associated environmental impact. In practice, mapping soybean trade to final consumption sectors presents several challenges. First, soybean is mostly consumed indirectly across the economy, in processed food, animal feed and livestock sectors, energy production, and industrial applications. As such, raw soybeans undergo various transformations along food, feed, and fuel supply chains, involving additional resource inputs and byproducts. Second, final products which use soybeans may be further traded; this may change their location of final consumption (e.g. where imported soybean is fed to animals and their meat is subsequently exported), and therefore also the ultimate responsibility for their environmental impact. Third, insufficient or inaccessible data on these pathways of processing and final consumption limits the traceability of soybean trade. Notwithstanding these challenges, this chapter attempts to evaluate consumption drivers of soybean trade and their associated water and land footprints. Such an exercise is highly relevant to guiding policies to reduce the environmental burden of soybean trade and has been overlooked in research and policy.

To attribute virtual water and land trade to final consumption sectors country-level import-related soybean resource use reported in the previous section are reconciled with country sectoral soybean use reported in FAO Food Balance Sheets (FAO, 2018). Where data on country-level soybean use are absent or deemed unreliable regional averages were used based on the author's calculations and estimates in the supplementary material of Bajželj et al. (2014). This analysis found that animal feed accounts for around three-quarters (73%) of water and land use associated with international soybean trade. Use of soybean in food products accounts for the remainder (24%) of virtual water and land use associated with soybean trade. The allocation of soybean to seed, energy, and loss of soybean in supply chains accounted for less than 2% of the soybean-related virtual water and land trade.

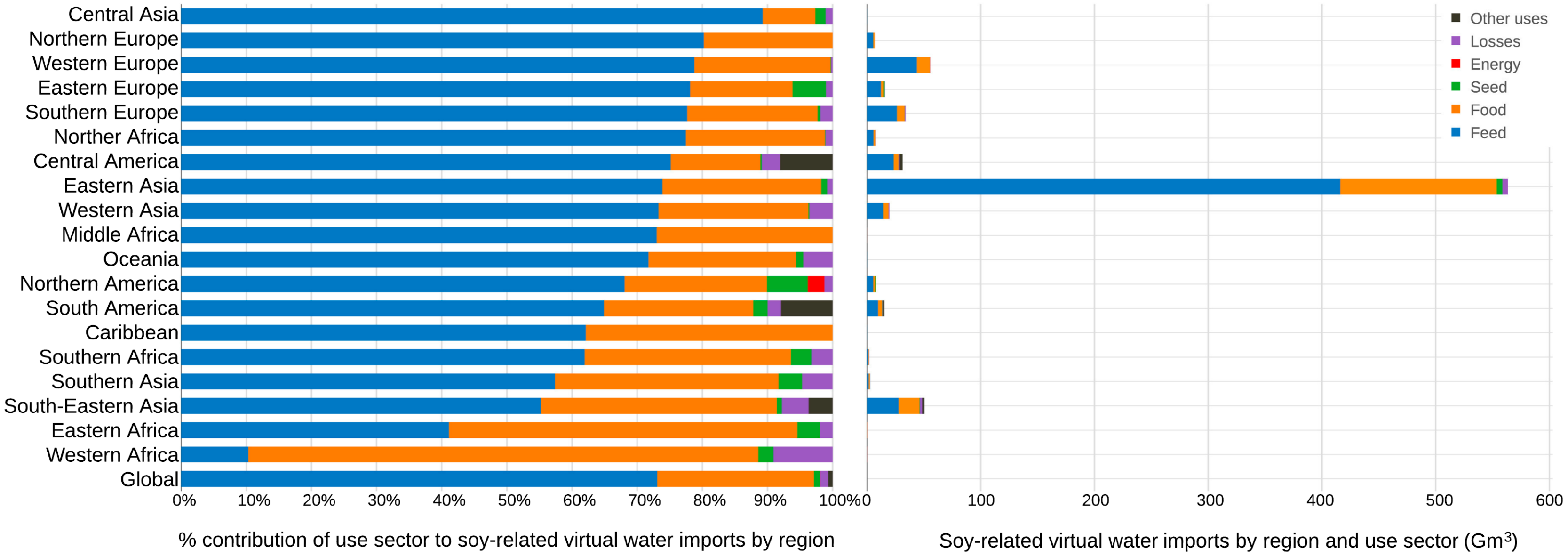

Fig. 3.5 Sectoral responsibility for virtual water use embodied in soybean trade

Sectoral responsibility for soybean-related virtual water imports in 2016 presented by region in relative (left) and absolute (right) terms.

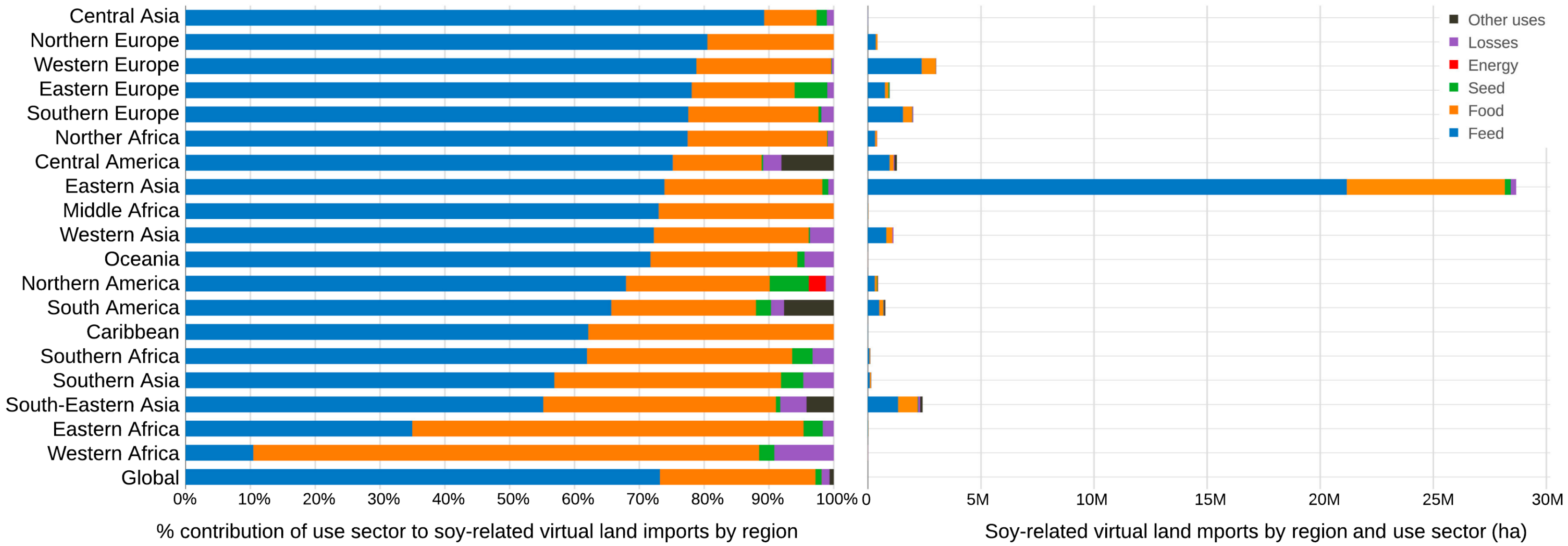

Fig. 3.6 Sectoral responsibility for virtual land are embodied in soybean trade

Sectoral responsibility for soybean-related virtual land imports in 2016 presented by region in relative (left) and absolute (right) terms.

Country variability in the use of soybean resulted in observable regional differences in sectoral responsibility for water use (Figure 3.5) and land area (Figure 3.6) linked to soybean trade. For example, the proportion of virtual water and land use attributable to animal feed use ranged from 10% in Western Africa to nearly 90% in Central Asia. However, in absolute terms, the allocation of soybean to animal feed in regions with high soybean imports (Central Asia, Europe and South America) explains the large overall responsibility of the animal feed for the virtual water and land use associated with soybean trade (Figures 3.5 and 3.6). Further differences can be observed in the allocation of, and associated environmental responsibility for, soybean imports for food (8–78% between regions). Still, direct use of soybean for food is concentrated in certain regions (Western Africa, Eastern Africa, Caribbean, South-East Asia) that import relatively small volumes of soybean compared with regions which import soybeans in large quantities for animal feed.

3.4 Discussion

Since 2000, the environmental burden of soybean production has become increasingly driven by international trade (Figure 3.1). This study has examined the water and land use embodied in international soybean trade to identify important actors, consumption drivers, and management priorities within this context. The analysis indicates that international trade is responsible for one-third of the water and land footprint of soybean production globally. The majority of this impact is driven by demand in China, the Netherlands and Brazil, for soybean grown in the US, Brazil and Argentina (Figure 3.2). In terms of major fluxes and countries, these findings agree with similar studies of soybean-related trade (*cf* Brown-Lima et al., 2010; Karstensen et al., 2013; WWF, 2014). By reconciling this analysis with information on soybean use within countries, animal feed is found to be responsible for the majority (73%) of soybean-related virtual water and land use, although sectoral responsibility varied between regions (Figure 3.5, Figure 3.6). This finding aligns with similar studies of sector-specific soybean use (*cf* Brown-Lima et al., 2010; WWF, 2014).

This study suggests a need for closer attention to the management of soybean-related resource use within the context of international trade, sectoral responsibility, and the dual impacts on water and land use. Trade represents a major pathway of human impact on the environment (Wiedmann & Lenzen, 2018). However, responsibility for the environmental impacts embodied in international trade are still routinely overlooked in water, energy, land, and climate policy (Afionis et al., 2017). Although accountability for environmental impacts is justified on the basis of national jurisdictions, the resource-related risks countries face and drive extend beyond their national borders, and therefore offer an important opportunity for resource management. The large trade of soybean, and associated virtual water and land from the USA to China might be considered a logical resource dependence since the USA experiences less water stress and higher land quality than China (WRI, 2015; Zhang et al., 2015). This same relationship holds for China's soybean imports from Brazil and Argentina, whereby soybean trade helps to satisfy China's domestic consumption whilst alleviating demand on its inadequate water and land resources. However, whilst the direction of soybean trade helps to moderate pressure on over-exploited water and land resources, the magnitude of soybean export represents a large, and inefficient use of natural resources when viewed from a sectoral perspective.

Animal feed is the primary consumption sector of globally traded soybean, and therefore, consumption of animal products is responsible for the vast water and land burden of soybean trade (see Figure 3.5, Figure 3.6). This consumption pathway represents an inefficient use of water and land resources due to several factors. First, around 60% of human-edible protein is lost in the conversion of soybeans to animal protein (Mottet et al., 2017). Second, ruminants and monogastrics, whether raised intensively or extensively, contribute towards significant additional natural resource use and environmental pollution (Garnett et al., 2017; Poore & Nemecek, 2018). Third, a continued increase in demand for animal products threatens to derail efforts to limit global temperature rise to 1.5°C above pre-industrial levels due to the role of livestock as a source of gaseous methane emissions and CO_2 emissions from land-use change and deforestation (Poore & Nemecek, 2018; Rogelj et al., 2018; Springmann et al., 2018). Although soybean for food is the second largest use sector of soybeans, direct allocation of soybeans for human consumption represents a far more efficient way of providing sustenance and nutrition to populations at a lower per capita environmental impact. For instance, soybean curd (i.e. tofu and byproducts) is less resource intensive than other sources of protein from meat and meat alternatives (Alexander et al., 2017; Smetana et al., 2015). Hence, measures to reduce meat consumption or shift towards direct consumption of soybean products would reduce the water, land, and wider environmental burden of soybean production for export, especially if such policies were undertaken in East Asia and Europe (Figure 3.5; Figure 3.6). Moreover, soybean only constitutes 4% of animal feed sources globally (Mottet et al., 2017). This suggests the opportunity for, and impact of supply-side measures which target soybean production efficiency are likely to have less impact on the total environmental burden of animal production when compared with dietary change (Mottet et al., 2017).

Any strategy to reduce the environmental burden of soybean trade must recognise the coupled nature of water and land use within agricultural production. By holding these impacts in simultaneous view decision makers can better manage the tensions, trade-offs and synergies arising from their management. Within the context of soybean trade, virtual water and land trade fluxes exhibit noticeable heterogeneity. The largest flux of virtual water trade connects the USA and China; whereas the largest virtual land flux arises from Chinese imports from Brazil (Figure 3.2, Figure 3.4). These discrepancies can be explained in part by the relative efficiency of water and land use and soybean production (Table 3.1). Although increased land use efficiency of soybean production is observed in all major exporting countries, water efficiency of soybean production declined in the USA between 2000 and 2016, resulting in a step-change increase in virtual water exports than virtual land exports around 2010 when the nation started to export more soybean to China (Table 3.1 and Figure 3.2). Although the underlying data used in this study does not reveal the cause of such trend, several factors might explain the reduced green water efficiency of soybean production observed in the USA between 2010 and 2016. First, the USA experienced several protracted droughts and warmer periods in soybean producing regions of the USA before and during this period (Rippey, 2015). As Rippey (2015) notes, 90% of US soybean production areas were located within areas experiencing drought during the 2012 drought in late July. Soybean yields are also acutely affected by extreme temperature above 30°C (*cf* Deryng et al., 2014; Schauberger et al., 2017; Schlenker & Roberts, 2009) which have become increasingly more common in the past decade in the USA (U.S. Global Change Research Program, 2014). It is plausible, that these changes reduced the green water use efficiency (i.e. crop per drop) of soybean production in the USA between 2010 and 2016 and therefore increased its overall green water footprint. Second, between 2007 and 2012, irrigated (i.e. blue water) agricultural land declined by over 300,000 hectares (USDA, 2019). This might imply a switch of soybean production from blue to green water sources during this period. Third, expansion of soybean production in the USA on marginal lands charactertised high erosion risk and vulnerability to drought is also observed over this period (*cf* Mladenoff et al., 2016; Wright & Wimberly, 2013), which might offer an additional explanation of the observed reduction green water efficiency of soybean production in the USA.

This chapter's findings highlight the need to examine the drivers of resource use from agricultural production (i) beyond the scope of producing regions, (ii) across the whole economy; and (iii) in relation to multiple environmental criteria. Although these have become active lines of inquiry in recent years, few models and assessments adopt all three. As a result, we lack a foundational understanding of risks and priorities across the global WEL system (Taherzadeh et al., 2018).

Limitations associated with the availability of data and depth of this analysis are important to note. First, the analysis relies on *estimates* of water and land use associated with soybean production, in lieu of nationally reported data. Second, soybean production and associated water and land use varies at a sub-national scale. By using only nationally-averaged data this analysis overlooks such heterogeneity. This limitation also applies to the weighted analysis of virtual water trade in relation to water stress, which exhibits large sub-national variation in both the exporting and importing nations (Liu et al., 2016; da Silva et al., 2016). Although sub-national production and resource use data are available, sub-national export data are often proprietary. Nevertheless, improvements in the availability of high-resolution trade data will help to improve the accuracy of estimating trade-related environmental impacts (*cf* Croft et al., 2018; Flach et al., 2016; Godar et al., 2015; Kanemoto et al., 2016; Moran & Kanemoto, 2016, 2017). Third, this analysis may underestimate soybean virtual water and land trade by overlooking soybean embodied in domestic exports of animal or other products. Here, nationally reported supply and use tables could help to capture indirect soybean trade within a multi-regional input-output analysis. Third, whilst this analysis focuses on green water production due to its primacy in soybean production, focusing on blue water used in soybean production might flag alternative policy priorities which can more readily be managed within the context of prevailing technology and pricing mechanisms (Distefano et al., 2018). Lastly, further attribution of soybean use to final consumption sectors would help to better identify specific products driving soybean production and trade (e.g. beef, pigs, chicken, and specific soybean food and industrial products) rather than entire sectors.

Notwithstanding these limitations, this analysis highlights the significant and increasing role of international soybean trade on water and land use, in individual countries and globally. The role of final consumers in these impacts is also discernible, as shown by the analysis of sectoral responsibility. Within the context of such globalised production and consumption systems, ‘supply-chain thinking’, previously uncommon in nexus scholarship, can help to quantify and assess responsibility for resource use. Although sustainable certification of soybeans has emerged in recent years, initiatives have had a trivial impact on the scale and severity of resource use associated with soybean production due to low levels of producer uptake (Garrett et al., 2016), consumer demand (Heron et al., 2018) and stakeholder consultation (Elgert, 2012). The winners and losers arising because of the water and land use embodied in soybean trade need to be evaluated at a macro and micro scale. Macro-scale assessment must capture the resource flow network underlying soybean trade and how this redistributes the environmental burden of countries and sectors (Distefano et al., 2018; D’Odorico et al., 2012; Sartori & Schiavo, 2015). Micro-scale assessment is required to ground-truth macro-scale findings by studying affected stakeholders at a local scale (Elgert, 2012, 2016), for example, to understand changes observed in the reduction in green water use efficiency in US soybean production in 2010 (see Table 3.1 and page 69).

To date, the research and policy agenda surrounding soy’s environmental impact have focused overwhelmingly on greenhouse gas emissions in the form of land-use change emissions or deforestation, especially in South America (Caro et al., 2018; Karstensen et al., 2013). Ostensibly, calls for ‘deforestation-free soybean supply chains’, such as Brazil’s moratorium to ensure deforestation-free soybean production (Gibbs et al., 2015), could be satisfied without addressing the large water and land footprint involved in soybean production. Hence, strategies which address the adverse environmental impacts of soybean must encompass combined water and land impacts as a major dimension (Damerau et al., 2016). Furthermore, it is important to examine critically whether patterns of agricultural consumption, production and trade represent an efficient allocation of natural resources within the context of food provision and national resource security.

3.5 Conclusion

The case study developed in this chapter informs the direction of this thesis research in terms of scope and methodology. In terms of scope, the findings of this chapter underline the importance of evaluating pathways of human influence across the WEL system within a globaland cross-sectoral. Whilst the complexities of soybean use sectors, illustrated in Figures 3.5 and 3.6, highlight the fragmented nature of resource use pathways which demand traceability from their origin of production to their origin of final consumption. Within this context, the deficits of physical environmental and commodity accounts are laid bare. Although such data enable MFA to be used to accurately evaluate flows of soybean (and other products) destined for direct final consumption, data are not yet available to adequately assess their consumption in other sectors. This necessities the estimation of final consumption sectors of products based on autonomous region assumptions (i.e. where all imported commodities are assumed to be produced using domestic recipes) (see Section 2.2.5). Moreover, within the context of trade, physical commodity accounts attribute resource flows based on bilateral data, which, as outlined on page 30, could potential result in final consumption countries and sectors being misidentified where supply chains involve multilateral trade. Since detailed physical environmental and commodity accounts are not yet available to meaningfully assess the influence of countries and sectors within complex and globalised production and consumption systems, MRIOA data, which offers greater coverage of relationships at this scale, is used to examine the thesis research questions (Section 1.4) in subsequent chapters. The next Chapter 4 continues to examine the contribution of international trade to pressures across the WEL system, but extends the scope of this assessment to distinguish domestic production, trade in macro-regions (e.g. West Europe or South America) and remote trade sources, across consumption in 189 countries and their sectors. This analysis is followed by a more comprehensive assessment of the overall contribution of food and other sectors to water, energy and land use in Chapter 5 and a study to locate these pressures within the context of multi-tiered supply networks in Chapter 6.

Chapter 4

The spatial footprint of the global water-energy-land system

> Studying the global, then, entails not only a focus on that which is explicitly global in scale, but also a focus on locally scaled practices and conditions articulated with global dynamics
>
> *Saskia Sassen, 2003*

4.1 Introduction

As an integrated approach, nexus assessment has the potential to expose the interconnected risks resource systems face and their exploitation drives (Bazilian et al., 2011). Such a cross-systems understanding of human-environment interactions has become increasingly important as economic development approaches multiple, interconnected planetary boundaries (Ehrlich & Ehrlich, 2013; O'Neill et al., 2018; Steffen et al., 2015). However, the increasing policy application of nexus scholarship - in the UN Sustainable Development Goals agenda (DIE, 2013; Nilsson et al., 2016; Weitz et al., 2014), national environmental policy (Cairns & Krzywoszynska, 2016; OECD, 2018; de Ridder et al., 2014), and industrial policy (Deloitte, 2017; Green et al., 2016; PwC, 2019) - demands careful examination of whether the priorities emerging from such studies direct sufficient attention towards critical drivers and sources of resource use, both in individual countries and globally.

Case studies have served as the dominant approach to assess source across the water-energy-land (WEL) system. However, boundaries for such analysis are usually established without a foundational understanding of major resource origins and risks across the WEL system which are global and cross-sectoral in scope. Consequently, policy priorities drawn from resource security assessment might simply be an artefact of the partial scope of analysis rather than a reflection of systemic risks to natural resource systems and the activities which they support (Srivastava & Lyla, 2014). As a result, many have called for resource use analysis to be broadened, sectorally and spatially, to encompass the totality of global water, energy and land use (Carmona-Moreno et al., 2019; Hoff & Gerten, 2015; Johnson et al., 2019; Staupe-Delgado, 2019; Sušnik, 2018; Taherzadeh et al., 2018; Vivanco et al., 2018b; Weitz et al., 2017; Wichelns, 2017). Only with this systematic overview can priorities for management of natural resources be meaningfully compared.

Attempts to broaden the scope of integrated environmental impact assessment remain limited to global models of the food sector (FAO, 2015; Keskinen et al., 2016; Lacirignola et al., 2014; Sušnik, 2018), cross-sectoral analysis of single countries or regions (Duan & Chen, 2017; Owen et al., 2018; Peng et al., 2019; Tukker et al., 2016), or global, cross-sectoral models which capture total national and sectoral resource use but do not distinguish its associated risk (Bijl et al., 2018; Velázquez et al., 2010; Vivanco et al., 2018a,b; White et al., 2018). Accordingly, there is a need for a flexible framework for resource use assessment which captures the major interactions and risks across the WEL system, and which is global and cross-sectoral in scope.

By developing a spatial and risk-weighted assessment of interactions between the world economy and global water-energy-land system, this chapter examines:

1. the level of country and sector dependence on global water, energy and land resources;
2. the severity and source of national and sectoral water, energy and land use and risk exposure; and
3. implications of national boundary setting for resource security assessment

Insights from this analysis can inform resource security assessment in three main ways. First, by studying how resource use connects different actors within the global economy, this analysis identifies the appropriate unit of spatial analysis (national, macro-regional or global) for the integrated management of consumption pressures on water, energy and land resources. Second, by linking consumption to source, this analysis reveals the main sources of resource extraction and risk embodied in national and sectoral supply chains, which in turn helps to identify otherwise unforeseen hot-spots for policy focus (Green et al., 2016). Third, this analysis brings into sharper focus the implications of national-scale resource security assessment of countries and sectors by revealing the resource use and risk ignored by only focusing analysis within national borders. In addition to contributing towards the identification of future research and policy priorities in resource security assessment, this chapter furthers understanding of national and sectoral dependence on, and exposure to, over-exploited, insecure, and degraded water, energy, and land resources.

The chapter begins by discussing the state of resource use assessment in relation to spatial coverage and boundary setting. This is followed by a summary of the analytical framework and indicators used to distinguish the national self-sufficiency and global inter-dependency of countries and sectors in relation to water, energy and land resources. A complementary schema of resource risk is developed in order to evaluate the severity of water, energy and land use embodied in national and sectoral supply chains, and the supra-national extent of these interactions. The insights from this analysis are reported at an aggregate scale to reflect on and respond to the need for a high-level understanding of the importance of different scales (national, macro-regional and global) at which resource use assessment may be undertaken. However, country case studies are used to illustrate noteworthy findings. The chapter concludes by discussing the relative importance of global-scale analysis to the study of the water-energy-land system in different contexts.

4.2 Methods

Boundaries for the analysis and governance of the WEL system should be informed by a comprehensive understanding of the total environmental burden of human activity as it emerges from a global and cross-sectoral analysis. However, current nexus assessment sets these boundaries *a priori*, often truncating accounting of water, energy and land use both sectorally and spatially (Taherzadeh et al., 2018). The partiality of nexus-based assessment methods and models, discussed in detail in Chapter 2, highlights the need for methods of nexus assessment which accommodate multi-regional and cross-sectoral analysis of national resource use. The previous chapter argues why MRIOA offers a preferred approach to MFA within this context (see Section 3.4). This chapter develops a modelling framework based on MRIOA accounting and data to evaluate the spatial distribution and severity of risks to water, energy and land use driven by countries and sectors. Since the main components of MRIOA are well documented in Chapter 2, it is necessary only to summarise the underlying principles, data and techniques associated with the specific analysis employed within this chapter.

4.2.1 Boundary setting and resource footprinting

The importance of boundary setting to the evaluation of country and sector resource footprints is exemplified by the numerous interlinkages and trade flows which redistribute the environmental burdens of production and consumption beyond national borders (Wiedmann & Lenzen, 2018). However, whilst the globalised nature of supply chains is often used to justify global-scale analysis of resource footprinting, the underlying production and resource origins of country and sector footprints remains poorly understood (Bijl et al., 2018). Moreover, the binary treatment of country or sector resource footprints as national or global ignores the significance of intra-regional country and sector inter-dependencies as a spatial unit of natural resource accounting and management. Distinguishing the source of non-domestic resource dependencies is important for several reasons. First, different scales of analysis entail vastly different levels of methodological complexity and data requirement for resource use assessment. Second, intra-regional resource footprinting implicates policy actors and communities that are overlooked in current global-scale assessment. Indeed, better alignment between units of resource use assessment and governance might exist at the macro-regional scale due to the plethora of bilateral and multi-lateral trade agreements which determine terms of trade between proximate nations (Morin et al., 2019; Taherzadeh, 2019a). Lastly, countries within a given region are likely to share similar environmental conditions which might compound the exposure of countries or sectors to resource risks in times of macro-regional resource degradation or scarcity. To address these gaps in understanding of the spatial distribution of country and sector resource footprints, this chapter evaluates water, energy and land use associated with countries and sectors at national, intra-regional (hereafter 'macro-regional'), and supra-regional (hereafter 'remote') scales.

4.2.2 Linking resource use to source

Conventional national resource footprinting, whether undertaken by physical trade flow analysis or MRIOA, produces a single, aggregate value which reflects the overall burden of a country's consumption within a given domain (water, energy, and land). However, by treating resource demand imposed in different countries as homogeneous, the resource footprint does not readily distinguish between the source and relative risk associated with a country's resource footprint. Ostensibly, two countries could have a similar overall resource footprint but exhibit a large variation in their exposure to resource-related risks owing to differences between the sustainability associated with the resource base on which they depend. This is illustrated in the study of VWT associated with soybean trade from low and high water stressed countries in Chapter 3. Moreover, two countries could face a similar level of resource-related risk, but from different sources; one country highly exposed to resource risks via domestic production and another from trade. By contextualising resource footprint assessment by risk severity and source it is possible to understand and manage the environmental burden of countries and sectors across different spatial scales. Such a disaggregation is employed in this chapter's analysis in order to establish the scale dependency of resource use and resource risks of countries and sectors across the WEL system. This also extends the resource risk analysis in Chapter 3 to the entire WEL system.

4.2.3 Modelling framework

Consumption-based water, energy and land footprints were calculated for 189 countries, and 19 global regions using the standard Leontief demand-pull model, described in Chapter 2 Section 2.2.5, across an MRIO table capturing inter-industry trade between their sectors. The resultant resource footprints and associated resource fluxes were partitioned in two ways. First, country and sector footprints were analysed in relation to three spatial boundaries: national, regional (e.g. South-East Asia or Western Europe) and remote. The regional scale was based on manual construction from UN et al. (2009) classifications e.g. South-East Asia or Western Europe. Second, indices designed to capture insecure water, energy, and land resource use were used to estimate the dependence of countries and sectors on high risk resource use at different spatial scales.

The partitioning of country and sector footprints by spatial scale was achieved by applying a series of masks - arrays of ones and zeros - to the resource requirements matrix of each country and region to assess their domestic (diagonal), non-domestic (off-diagonal), and macro-regional (manually constructed from UN et al. (2009) classifications) consumption-based resource footprint. This revealed the importance of national, macro-regional and global boundary setting for resource use assessment of countries and sectors.

The partitioning of country and sector by resource-related risks followed a similar approach. Within the context of this assessment, resource risk is defined as:

Dependence of countries, sectors or consumers on natural resource use characterised by current environmental and/or political insecurity.

This narrow conception of resource risk reflects the limited availability of data pertaining to other potentially more meaningful determinants of resource insecurity for countries and sectors contained within this assessment, such as adaptive capacity (Folke, 2016; Govindan et al., 2014; Tukamuhabwa et al., 2015), time frame of resource insecurity (Behzadi et al., 2018; Heckmann et al., 2015; Snyder et al., 2016), and organisational influence (Fayezi et al., 2012; Friday et al., 2018; Varsei et al., 2014), which might help to imply the extent of risk propagation, risk duration, risk sharing and related risk exposure of actors across supply networks. Indeed, the nature of resource insecurity and its relation to risk is multifaceted, as noted by past attempts to characterise water security (Cook & Bakker, 2012; Jepson et al., 2017; Kumar, 2015), energy security (Cherp & Jewell, 2014; Le et al., 2019; Månsson et al.,

2014) and land security (Elgert, 2016; FAO, 2011; Lambin & Meyfroidt, 2011). Lack of access to natural resources also affects the provision of goods, services and basic needs depending on the resource system concerned, preventing a unifying theory of resource insecurity and its impacts (Wutich & Brewis, 2014). Resource ownership and governance, whilst critical in terms of resource access, are also not fully captured in prevailing risk indices. Nevertheless, given the limited understanding of how resource-related risks connect different actors across the global WEL system (Wiedmann & Lenzen, 2018), the explanatory power of an assessment borne from a simple definition of resource security can still be instructive for the identification of new research and policy priorities surrounding sustainable resource use. Attempting such assessment can help to identify important methodological challenges and data gaps for the assessment of supply chain resilience, and the resource security of consumption patterns across a large number of countries and sectors. This is an increasingly important priority for national governments and businesses (WEF, 2019).

The resource risk indices used in this assessment, described in Section 4.2.4 capture qualitative differences in the sustainability and stability of water, energy and land use in different country contexts. This enables 'risk tagging' of resource flows embodied in national and sectoral supply chains (Figure 4.1). To help convey and compare the resource risk profile of different countries and sectors, resource risk categories, 'high', 'medium', and 'low' were assigned to countries based on whether they ranked in the top, middle, or bottom third of resource risk indices respectively. An overview of this methodological procedure and the data concerned is summarised in Figure 4.1.

Formulaically, the source and severity of country and sector resource footprints are calculated as follows:

$$\underset{h,m,l}{F_r}{}_{c=1}^{c=189} = \overbrace{\underset{h,m,l}{f.\ u_r}.[\mathrm{A}_c x_c + y_c]}^{DomesticRF} + \overbrace{\underset{h,m,l}{f.\ u_r}.[\sum_{s\neq c\neq t} \mathrm{A}_s x_s + y_s]}^{Macro-regionalRF} + \overbrace{\underset{h,m,l}{f.\ u_r}.[\sum_{t\neq s\neq c} \mathrm{A}_t x_t + y_t]}^{RemoteRF} \tag{4.1}$$

where $F_{r_{h,m,l}}$ refers to the high, medium and low risk footprint of a given country, c, for a given resource r (i.e. water, energy or land); x is a column vector of intermediate output in a given country (x_c), its macro-region (x_s) or its remote trading partners (x_t); A is the direct requirements matrix of a given country ($\mathrm{A_c}$), its macro-region ($\mathrm{A_s}$) or its remote trading partners ($\mathrm{A_t}$); y_c is the final demand for domestically produced commodities and services in a given country, c, whereas y_s and y_t represent the final demand of country c for production in its macro-region and remote trading regions; u represents an intensity coefficient for a given resource use, r, in each sector; and, $f_{h,m,l}$ refer to a mask vector (of ones and zeros) to filter high, medium and low risk production and associated resource use, as defined by Equation 4.2. Equation 4.1 can be manipulated to make a macro-region or sector the subject of assessment, as shown in Figures 4.5 and 4.8 respectively.

Resource risk masks were calculated to filter country resource footprints by partitioning raw country resource risk index values, described in Section 4.2.4, into high, medium and low risk:

$$\underset{0,1}{f_c} = [RI_c \geq \frac{RI^{max}.i - RI^{max}}{3}].[RI_c \leq \frac{RI^{max}.i}{3}] \tag{4.2}$$

where f_c is a 'mask' value of '0' or '1' to indicate whether the production of a country, c, falls within 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 resource footprints; and RI is the raw index value data for a country, c. Equivalent sectoral masks were computed for sectors on the assumption that they faced the same level of resource risk assigned to their country; this was necessary given the lack of sector-specific resource risk data available.

An overview of this methodological procedure and the data concerned is summarised in Figure 4.1. A worked example is provided in Section 4.3.3 to demonstrate the procedures employed, the data arising, and a potential application of findings from the risk and spatially partitioned resource footprint of countries and resources.

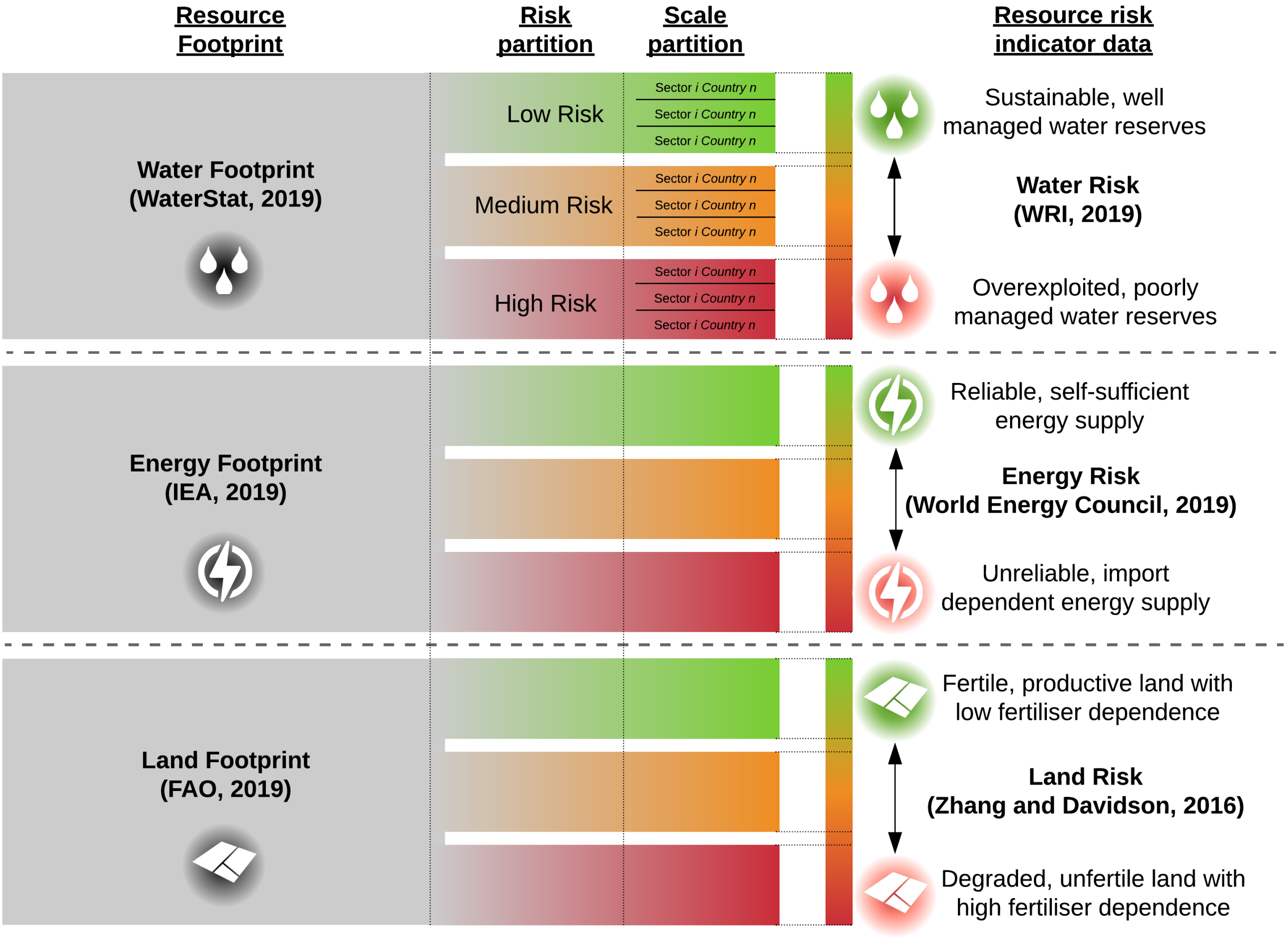

Fig. 4.1 Partitioning resource footprints by spatial scale and risk level
Conceptual diagram illustrating the workflow and data involved in risk and scale partitioning of country and sector resource footprints with references to resource use and risk datasets.

4.2.4 Data

Numerous multi-regional input-output (MRIO) databases exist for the purpose of economy-wide resource footprinting. Within this chapter (and thesis) the Eora (2019) MRIO database, developed by Lenzen et al. (2012a), is used for its superior sectoral resolution, temporal coverage, and integration with environmental datasets. Other MRIO databases are summarised in Section 2.3 for completeness. The full and latest version of the Eora (2019) captures production, consumption and trade relationships between 189 countries and their sectors (14838 in total) between 1990 and 2015. Section 7.3 describes how the Eora (2019) MRIO database is constructed and outlines the caveats associated with its use.

Several criteria informed the selection of resource use and resource risk indicators. These included (i) country and sectoral coverage, (ii) scope in relation to pressures facing water, energy and land systems, (iii) data access, and (iv) data format. An ideal indicator is one with good alignment with the countries and sectors within the Eora (2019) database, meaningful coverage of pressures on resource systems, reliance on open-access and time-proofed data, and minimal processing required before integration with the model.

A concordance of physical environmental accounts of sectoral resource use with national economic accounts in the Eora (2019) database by Lenzen et al. (2012a) provided an integrated framework for undertaking water, energy and land footprinting of countries and sectors without the problems of double counting and boundary setting common to use of external environmental datasets (OECD, 2003). However, since data to infer risks associated with water, energy and land use are not readily integrated into MRIOA databases, these were sourced from external sources and linked to the model following the steps explained in Section 4.2.3. The raw and categorised resource insecurity indices for countries can be found in Taherzadeh (2020).

Water use data were sourced from WaterStat (2019), the world's most comprehensive water footprint database, which compiles agricultural and industrial water use data for countries and sector. The database, developed by Hoekstra & Wiedmann (2014), relies principally on data from the UN FAO which reports member countries' agricultural water use through a yearly survey administered by their national authorities (Mateo-Sagasta & Salian, 2012). The water use of industrial commodities relies on data from FAO (2020) and Eurostat (2020) and is further elaborated in Hoekstra & Mekonnen (2011). A given sector's production-based water footprint accounts for its direct blue water use (from groundwater and aquifers) and green water use (precipitation and evapo-transpiration); these were aggregated to evaluate the total consumption-based footprint of countries. Since WaterStat (2019) only covers national and sectoral water use between 1990-2005, data were scaled by annual sectoral production, consumption and trade expenditure in the Eora (2019) database in order to calculate consumption-based water footprints for other years. Many indicators have been proposed to evaluate the sustainability of water use. Measures of blue and green water scarcity, water quality, environmental flow requirements, economic access to water, and water regulation standards have received greatest attention within scientific and policy communities (Vollmer et al., 2016). Within this assessment, an indicator of 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. Although use of a single water risk indicator may not reflect the multi-dimensional nature of threats associated with national water use, there are several justifications for its use. First, in contrast to green water, blue water sources are often non-renewable and so their over-exploitation poses a more acute threat to water users. Second, as a point source resource stock, blue water can be readily managed via pricing and regulation. Third, blue water scarcity is the agreed metric to assess progress against the water-related UN Sustainable Development Goals (Vanham et al., 2018); this enables direct policy application of the analysis within this study.

Energy use data were sourced from the International Energy Agency which reports total energy use by sector from twelve sources: natural gas, coal, petroleum, nuclear, hydroelectric, geothermal, wind, solar, tide, wave, biomass, and waste based on annual questionnaires of countries (IEA, 2019). Energy risk data were sourced from the World Energy Council (2018) Energy Index which ranks countries' energy security according to their effective management of primary energy supply from domestic and external sources, reliability of energy infrastructure, and ability of energy providers to meet current and future demand. In contrast to the water and land risk indicators which measure the environmental sustainability of resource, the energy risk indicator did not measure the environmental sustainability of national energy use since such a metric (such as the proportion of renewable energy production in national energy mix) does not meaningfully capture energy (in)security and related risks.

Land use data were compiled by the UN Food and Agriculture Organization (FAO, 2019) and capture the extent of land under cultivation for 172 crops based on data reported by member countries' national authorities through annual questionnaires of "land use, irrigation and agricultural practices". Land risk data is based on a the Sustainable Nitrogen Management Index (SNMI), developed by Zhang & Davidson (2016) based on data from FAO (2019) and compiled by Yale University (2019) for 2010. The SNMI provides a proxy for the productivity *and* sustainability of agricultural land use, based on (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).

An unclassified category was assigned to resource-related use in countries which were not measured by the risk indices used. Overall, 0.42% of global water use, 3.78% of global energy use and 2.07% of global land use were unclassified by the risk indicator datasets used. Meanwhile, the lack of temporal concordance between resource use and risk data and economic accounts meant the assessment of national water, energy and land footprints in this chapter (and thesis) assumed no change in resource efficiency or resource insecurity for time periods where data is missing (e.g. for water footprints after 2005 or water and land insecurity after 2010). However, such assumptions can be relaxed as the temporal coverage of economic and environmental data improves Dietzenbacher et al. (2013a).

4.3 Analysis

This section presents the decomposition of country and sector water, energy and land footprints by resource risk and spatial scale. Section 4.3.1 presents a resource footprint and risk profile of countries and sectors in relation to water, energy and land. Section 4.3.2 distinguishes the contribution of domestic and non-domestic resource use within this context and identifies key sources of influence in relation to country and sector resource use dependence and risk exposure.

4.3.1 Country and sector risks across the WEL system

Profiles of country exposure to resource risk vary with respect to water, energy, and land. Figure 4.2 presents the overall distribution of national dependence on low, medium and high risk water, energy, and land use for all 189 countries analysed. The risk profile of country water and energy footprints appear somewhat closer than land to what may be desirable - a high level of dependence on low risk resource use and low level of dependence on high risk resource use - as illustrated by the key in Figure 4.2 - but do not imply a high proportion of countries are water or energy secure. The risk profile of land use suggests lower levels of national dependence on low risk land use and higher levels of dependence on high risk land use. All three resource risk profiles exhibit a bi-modal distribution which highlights a partition of countries into one of two groups: resource secure and resource insecure.

Whilst the overall landscape of national resource risks is concerning, several countries are noteworthy within this context. Figure 4.3 illustrates the absolute volume of high risk and low risk water use (in Gm^3), energy use (in TJ) and land use (ha) embodied in (A) national (n=189) and (B) macro-regional (n=19) consumption. This global landscape of resource-related dependence captures several features of national exposure to resource risk. First, many countries exhibit greater dependence on high risk resource use than low risk resource use, as indicated by their position right of the 1-1 lines of equality in Figure 4.3; this corresponds to water use in 39 countries, energy use in 32 countries, and land use in 81 countries. Several countries even appear to suffer a double burden (n=22) or triple burden (Algeria, Lebanon, Morocco and Pakistan), dependence on high risk resource use across more than one resource. However, risk-based profiling of individual countries' resource footprints reveals that most countries experience both different sources and levels of exposure to water, energy and land risks. For example, the USA exhibits the highest dependence (92%) of any country on high risk land use, chiefly (96.4%) from its own domestic production; is moderately (around 50%) dependent on high risk water use, mainly from Mexico (34%), India (27%) and Pakistan (13%); but relies primarily (86.6%) on low risk energy use. Nevertheless, in absolute terms, the USA's high risk energy use is among the highest of any country modelled, as shown in Table 4.1. In contrast, India exhibits minimal (>1%) exposure to high risk land use but is the most highly dependent country on high risk water use (94.5%), almost wholly (99%) due to its own domestic high risk water use.

Table 4.1 Top five countries by high risk resource footprint

High-risk water footprint	High-risk energy footprint	High-risk land footprint
India	Thailand	USA
Pakistan	Egypt	Brazil
Mexico	Pakistan	Ukraine
Turkey	USA	Canada
Iran	Bangladesh	China

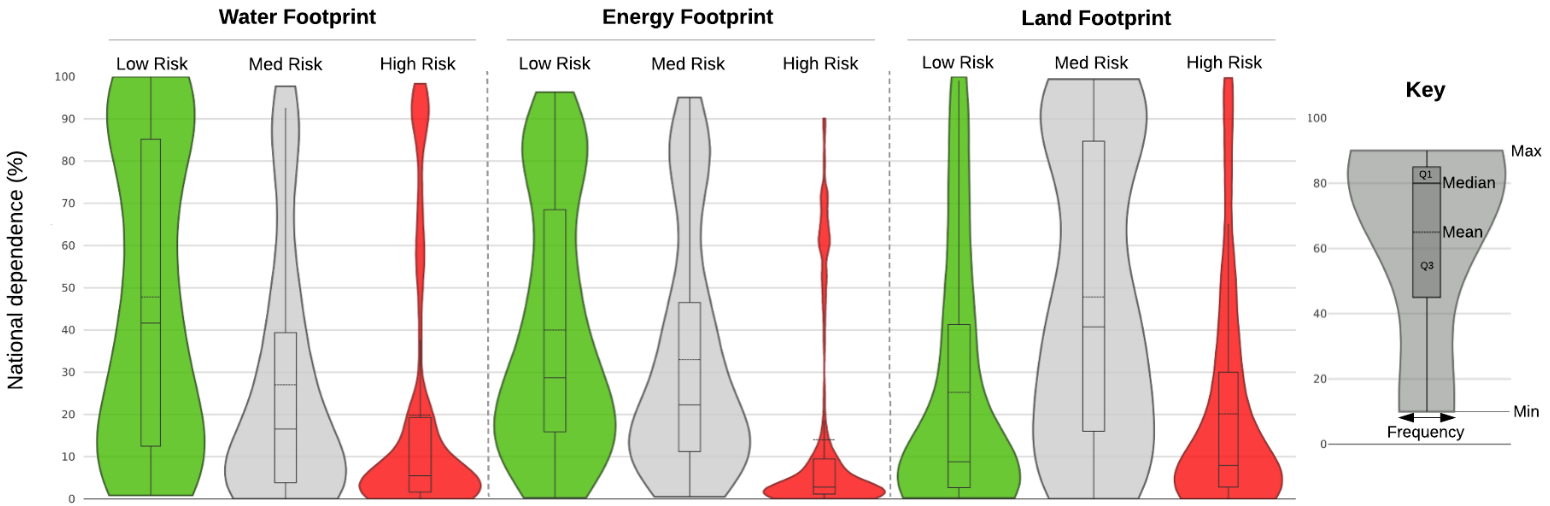

Fig. 4.2 Profile of water energy and land use

Violin and box plots showing the distribution of national consumption (n=189) met by water, energy,and land resources of low and high risk. The width of each violin represents the frequency of countries at a given level of resource risk (green=low, grey=medium, red=high) and proportion of national dependence. Box plots represent the inter-quartile range (Q1, median, Q3). Dashed black lines denote the mean national dependence on water, energy, and land resources at low and high risk.

The advantages of a risk-based approach to resource footprinting is also apparent when comparing two countries with a similar overall footprint, indicated by circle size in Figure 4.3A. The USA and China have similar overall energy and land footprints, however China exhibits lower reliance (6.2%) on low risk energy compared with the USA (86.6%) and the US is more highly exposed (92.6%) to high risk land use than China (4.2%). This discrepancy is explained by (i) energy and land use in China being classified as medium risk, (ii) land use and energy use in the USA being classified as high risk and low risk respectively; and, (iii) energy and land footprints in both countries being imposed mainly domestically. However, The uniform treatment of national resource use as either low, medium or high risk ignores these sub-national differences and their combined influence on the resource insecurity of domestic production and trade pathways (Lenzen et al., 2013a). In large countries, where resource security exhibits large internal variation, integrating sub-national resource use and risk data into macroeconomic assessment of resource insecurity is potentially valuable (Guan & Hubacek, 2007).

In other cases, trade plays a much greater role in the transmission of resource insecurity, as shown in Section 4.3.2. Ranking countries in terms of their high-risk water, energy, and land footprint, instead of their overall footprint, as shown in Table 4.1 reveals countries which have received less attention in resource-related research and policy to date. Although not featured in the top countries by absolute resource footprint (USA, China, India, Brazil, Russia and Japan), Pakistan, Mexico, Turkey, Iran, Thailand, Egypt, Bangladesh, Ukraine and Canada are found to be globally important within the context of high risk resource use (Table 4.1).

At a macro-scale, global regions were also found to be acutely exposed to water, energy and land risk (Figure 4.3). Central, Southern and Western Asia showed the highest dependence, on high risk water use (70-90%). In terms of energy, Northern Africa was highly exposed to sources of high energy risk (>75%), however the remaining 18 regions were more energy secure with dependence on high risk energy ranging between 0.4 and 20.3% (mean: 7.14%). The Americas (Northern, Southern, and Central America) and Europe (all regions) were highly exposed to land-related risk; meanwhile regions in Asia and Africa had low levels of dependence (<13%) on high risk land use.

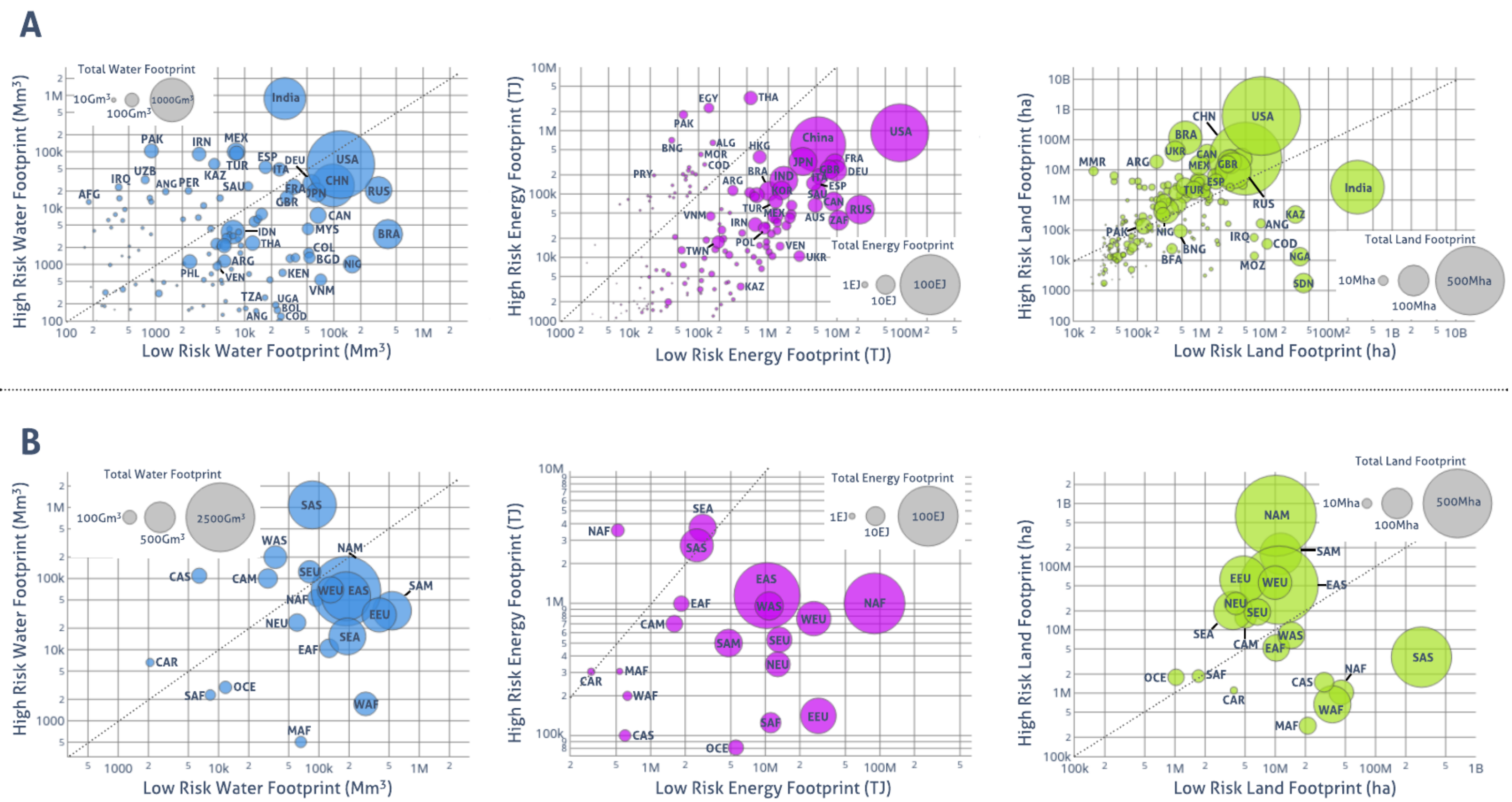

Fig. 4.3 Level of national and macro-regional resource risk

National (A) and macro-regional (B) water, energy, and land footprints decomposed into low risk (x-axis) and high risk (y-axis) components, displayed on a log scale. Circle size represents the overall resource footprint of a nation or region. Macro-region abbreviations - NAF: Northern Africa, EAF: Eastern Africa, MAF: Middle Africa, SAF: Southern Africa, WAF: Western Africa, CAR: Caribbean CAM: Central America, SAM: South America, NAM: Northern America, CAS: Central Asia, EAS: Eastern Asia, SEA: South-eastern Asia, SAS: Southern Asia, WAS: Western Asia, EEU: Eastern Europe, NEU: Northern Europe, SEU: Southern Europe, WEU: Western Europe, OCE: Oceania.

Important countries in relation to resource use and associated risks can also be identified by weighting countries' risk-based footprints in relation to the size of their economy and population to assess the average resource burden of (i) an individual consumer and (ii) a dollar spent and (ii) in each country. This analysis reveals major differences between the influence of economic and demographic change on resource use in different countries and global regions. Table 4.2 shows the top 15 countries[1].

Table 4.2 Top 15 countries by high risk water, energy and land footprint per capita

Water Footprint per capita (m^3)		**Energy Footprint per capita (MJ)**		**Land Footprint per capita (ha)**	
7539	USA	288,931	USA	2.03	USA
2648	Russia	195,895	SouthAfrica	1.03	Sudan
2355	Ukraine	192,331	SouthKorea	0.98	Ukraine
2192	Brazil	173,049	Japan	0.95	Russia
1969	Argentina	165,769	France	0.61	France
1894	Spain	160,611	Russia	0.60	Germany
1886	France	153,786	UK	0.57	Brazil
1840	Germany	150,189	Germany	0.55	Spain
1647	Thailand	126,187	Spain	0.48	Japan
1576	Italy	118,963	Italy	0.47	UK
1551	Japan	72,231	Thailand	0.46	Thailand
1476	UK	71,501	Ukraine	0.44	Argentina
1447	Sudan	67,103	Turkey	0.42	Italy
1442	SouthKorea	66,015	Argentina	0.42	Turkey
1397	Colombia	65,913	Iran	0.41	China

Table 4.3 shows GDP-weighted water, energy and land footprints across major economies[2]. The high GDP-weighted water, energy and land footprints of India, China, and Russia suggest their economic development is a major driver of resource demand across the WEL system. Equivalent calculations for high risk resource use reveals other economies of importance; Turkey, India, Mexico, Spain and Italy in the case of high risk water use; Indonesia, France, Spain, and Turkey in the case of high risk energy use; and, Brazil, USA, Canada, Mexico and France in the case of high risk land use.

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[1] Countries with a population <0.5% of the global total were excluded from Table 4.2 to reveal only those countries whose per capita resource footprint figures were significant) by high risk water, energy and land footprint per capita. The USA exhibits the highest per capita high risk water, energy and land footprint. Other high-income countries also tend to have the highest resource footprint per capita in relation to high risk water, energy and land resources (Table 4.2)

[2] Major economies were defined as any country which contributes more than 1% to global GDP

Table 4.3 GDP-weighted high-risk water, energy and land use among major economies

Water Footprint per unit GDP (m^3/\$)		Energy Footprint per unit GDP (TJ/\$)		Land Footprint per unit GDP (ha/\$)	
0.50	India	12.3	Russia	164.3	India
0.35	Indonesia	11.8	India	72.4	Russia
0.21	Brazil	9.9	China	65.6	China
0.20	Russia	9.9	SouthKorea	62.6	Indonesia
0.14	USA	7.4	Indonesia	54.4	Brazil
0.13	Mexico	6.3	Turkey	39.6	Turkey
0.13	Turkey	5.5	USA	38.6	USA
0.11	China	5.3	Canada	33.4	Mexico
0.07	SouthKorea	5.1	Mexico	20.8	Canada
0.07	Canada	4.8	Brazil	19.8	Australia
0.06	Spain	4.4	Australia	19.5	SouthKorea
0.05	Australia	4.2	Japan	17.0	Spain
0.05	France	4.0	France	15.0	Germany
0.05	Germany	3.9	Spain	14.8	France
0.05	Netherlands	3.8	Netherlands	13.5	Netherlands

Individual sectors exhibited a similar profile of water, energy and land risk to countries owing to the contribution of their production, consumption and trade dependencies to each country’s overall demand. However, the granularity of sector-level data enables identification of specific consumption and production activities responsible for the majority of global resource use and risk. These insights are examined in detail in Chapter 5 on sectoral priorities across the WEL system, so are only summarised here. A small proportion of sectors exhibited low levels (<10%) of exposure to high risk water use (9.9%), high risk energy use (12.3%) and high risk land use (2.6%). However, in line with the country-level analysis, sectors were found to be more dependent on high risk land use than water or energy use and least exposed to high risk energy use of all three resource footprints analysed. Large within-country differences between sectors in terms of resource use and risk profile existed. These disparities, imply scope for a triage-based approach to nexus-based analysis and management within countries, which is explored in Chapter 5.

4.3.2 Domestic, macro-regional and remote resource dependencies

This section highlights the importance of different spatial scales to the resource use and resource risk of countries and sectors modelled. In contrast to single (i.e. global) or two-tiered (i.e. domestic and non-domestic or domestic and macro-regional) assessments, country and sector resource use is evaluated at three spatial scales: domestically, macro-regionally, and remote (i.e. beyond the region a country is situated).

Countries and sectors are found to be highly dependent on non-domestic water, energy and land use. A significant number of countries are more dependent on water (n=72), energy (n=81), and land use (n=81) abroad than in their own country. Many countries rely almost entirely (>90%) on water (n=29), energy (n=52), and land (n=45) resources in countries to satisfy their domestic demand for goods and services. Although the importance of non-domestic resource varies more greatly for sectors than countries, on average sectors exhibit a high dependence on water (median = 55.1%, mean = 53.7%), energy (median = 36.4%, mean = 43.5%), and land use (median = 80%, mean = 65.7%) in countries other than their own. Figure 4.5 illustrates how the contribution of international trade to sectoral footprints has varied between 2000 and 2015. Over this period, sectors became noticeably less dependent on non-domestic water use, slightly more dependent on non-domestic energy use and maintained a high dependence on non-domestic land use. This can be seen by tracking the median and mean contribution of non-domestic water, energy and land use to sectors' overall water, energy and land footprints in Figure 4.4.

Although the borderless nature of national and sectoral resource use and resource risk is well documented (*cf* Bruckner et al., 2012; Chaudhary & Kastner, 2016; Krausmann et al., 2017; Lenzen et al., 2012a; Taherzadeh et al., 2018; Wiedmann & Lenzen, 2018; Wood et al., 2014), the contribution of macro-regional and remote resource use to this remains poorly understood (Wiedmann & Lenzen, 2018). By further partitioning non-domestic resource fluxes embodied in national consumption and sectoral demand by macro-regional and remote sources such evaluation is possible. Figure 4.5 illustrates which of these scales (domestic, macro-regional or remote) account for the greatest proportion of national resource dependency and exposure to resource risk.

For many countries domestic water, energy and land use is greater than non-domestic macro-regional or remote resource use; this is illustrated by the yellow in Figure 4.5. Although macro-regional dependencies were not the most important factors for most countries, they still accounted for a modest proportion of overall national water use (median = 3.9%, mean = 7.4%), energy use (median = 5.5%, mean = 9.9%) and land use (median = 3.9%, mean = 8.4%). The importance of national resource use to national resource footprints does not imply national self-sufficiency in water, energy and land use for countries, but simply indicates national borders are an important unit of resource use assessment and management.

Moreover, for several countries, remote production accounts for the greatest source of their total water use (Canada, Chile, South Sudan), energy use (Botswana, Laos, Luxembourg, MacaoSAR, Namibia, and Swaziland) and land use (Chile, Côte d'Ivoire, New Zealand and Zimbabwe) footprint. International trade also represents the greatest source of national exposure to risks across the WEL system, as shown by the importance of remote and - to a lesser degree - macro-regional, production sources to countries' water, energy and land risks in Figure 4.5 (right hand maps).

International trade is associated with 19.8%, 30.5% and 22.5% of high risk water, energy and land use respectively. For most countries international trade is (i) a greater source of water risk (n=159), energy risk (n=153) and land risk (n=172) than domestic production and (ii) the only source of national exposure to water risk (n=150), energy risk (n=150), and land risk (n=166). The relative importance of non-domestic resource dependency for a given country is a product of its domestic resource risk, domestic self-sufficiency and the resource risk associated within its major trading partners. To this end, it is possible for a country to exhibit the greatest exposure to resource risk from remote sources, because of the relatively low risk associated with both its own domestic resource use, and the resource use in its neighbouring countries. Equally, countries can be more highly exposed to high risk resource use domestically if their own resource risk is classified as 'high risk' *and* their virtual import of high-risk resource use through trade is lower than their internal resource footprint. Figure 4.6 shows the major role international trade plays as a conduit of sectoral resource use and risk across the WEL system. Since this analysis covers many thousands of sectors, Figure 4.6 is designed to convey general trends in the resource origins of sectoral resource use and risk. The radial axis used allows such an aggregated view by creating a 'fan' comprising the levels of non-domestic domestic resource use and risk in each sector, the spread of which indicates the importance of international trade across the world economy.

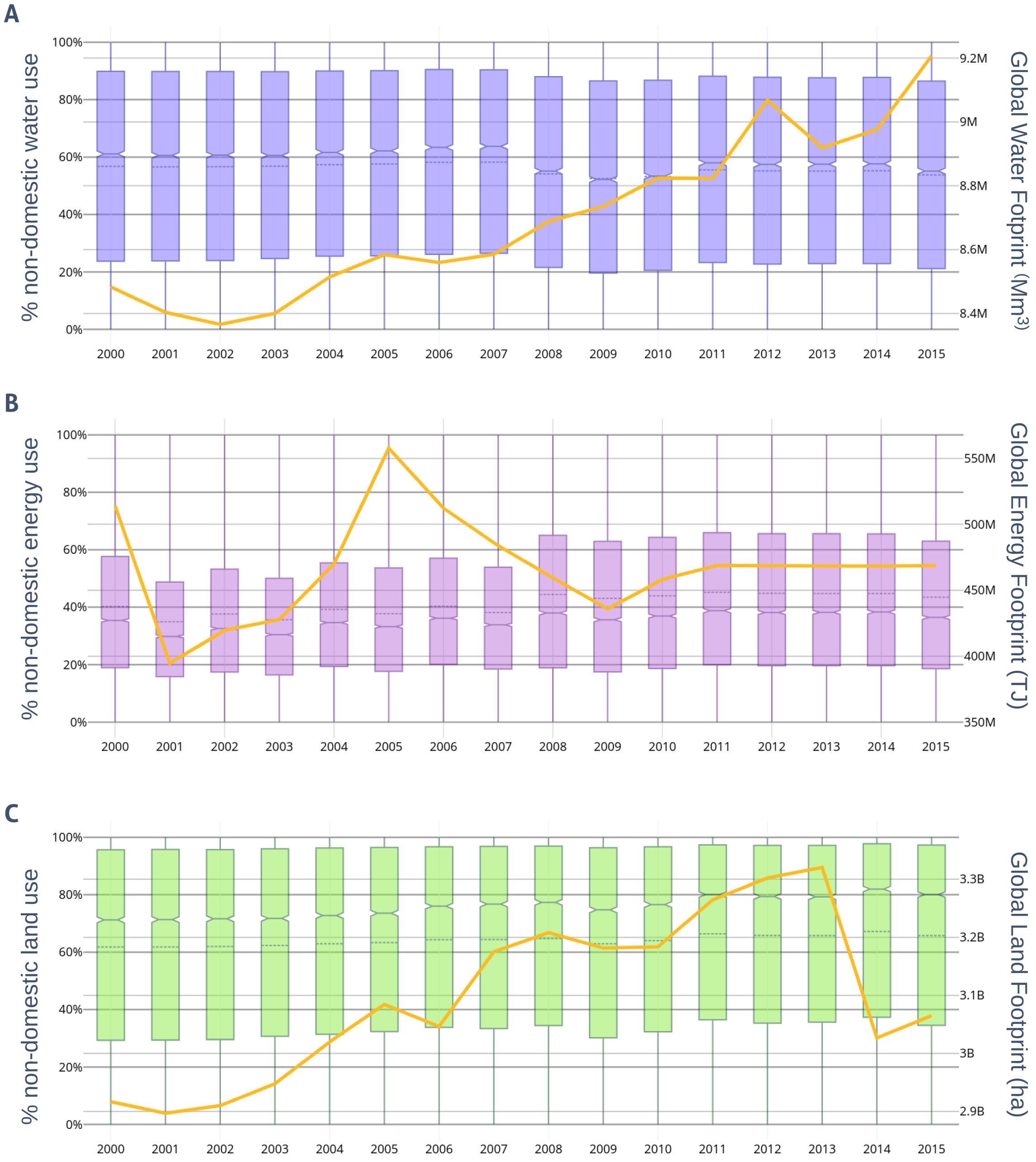

Fig. 4.4 Virtual water, energy and land use between 2000 and 2015

Box plots illustrating the percent of sectoral dependence (left y-axis) on non-domestic (A) water, (B) energy and (C) land use for all 14838 sectors in the Eora (2019) database, based on the proportion of macro-regional and remote sectoral resource use to domestic resource use, as described in Equation 4.1, between 2000 and 2015. Dashed lines denote mean values and solid lines denote median values. The total non-domestic water (A), energy (B) and land (C) use associated with global consumption (right y-axis, and yellow line) is shown over this period.

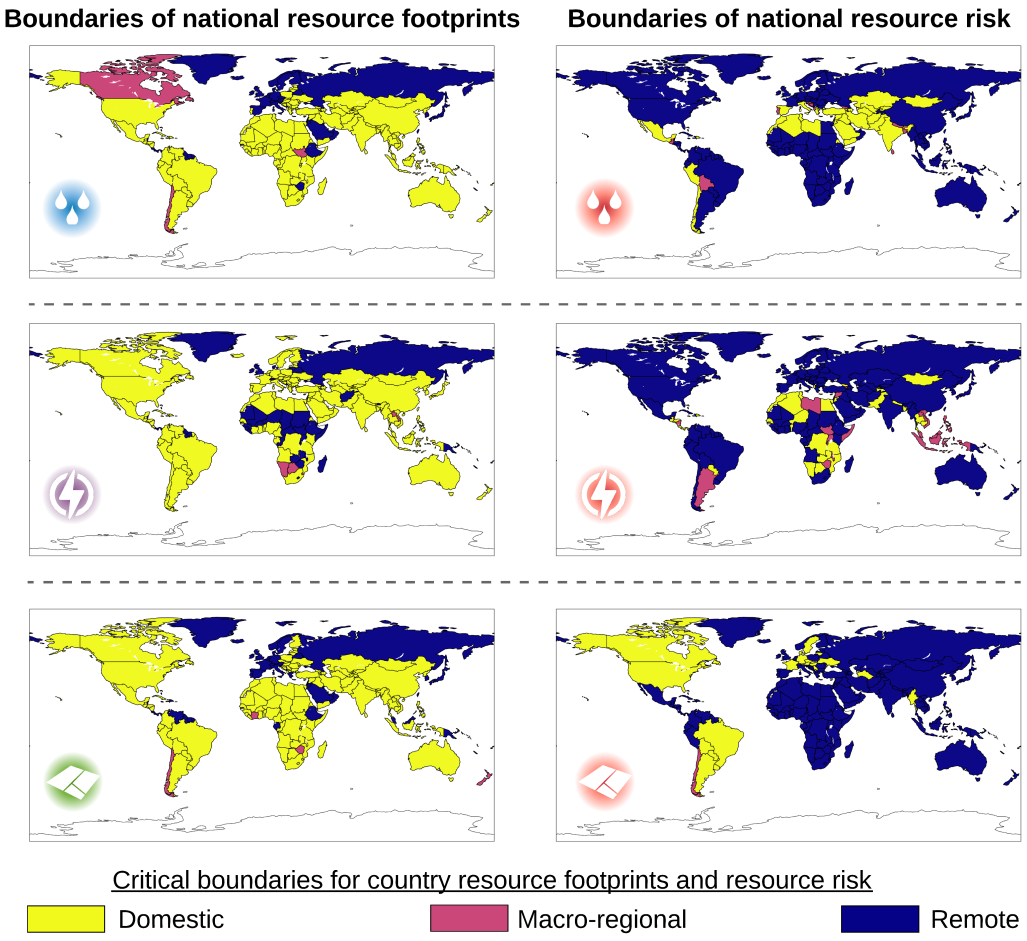

Fig. 4.5 Major sources of country resource supply and risk across the WEL system

Chloropleth maps with shading of countries according to their most important resource origin (domestic = yellow; macro-regional = pink; remote = blue) on water, energy and land use. Left hand figures relate to important boundaries of overall national resource footprints. Right hand figures relate to important boundaries of national high risk resource dependence. Country colouration is based on which resource origin (i.e. domestic, macro-regional or remote) accounts for the largest share (i.e. more than 33.3%) of its resource use or risk footprint.

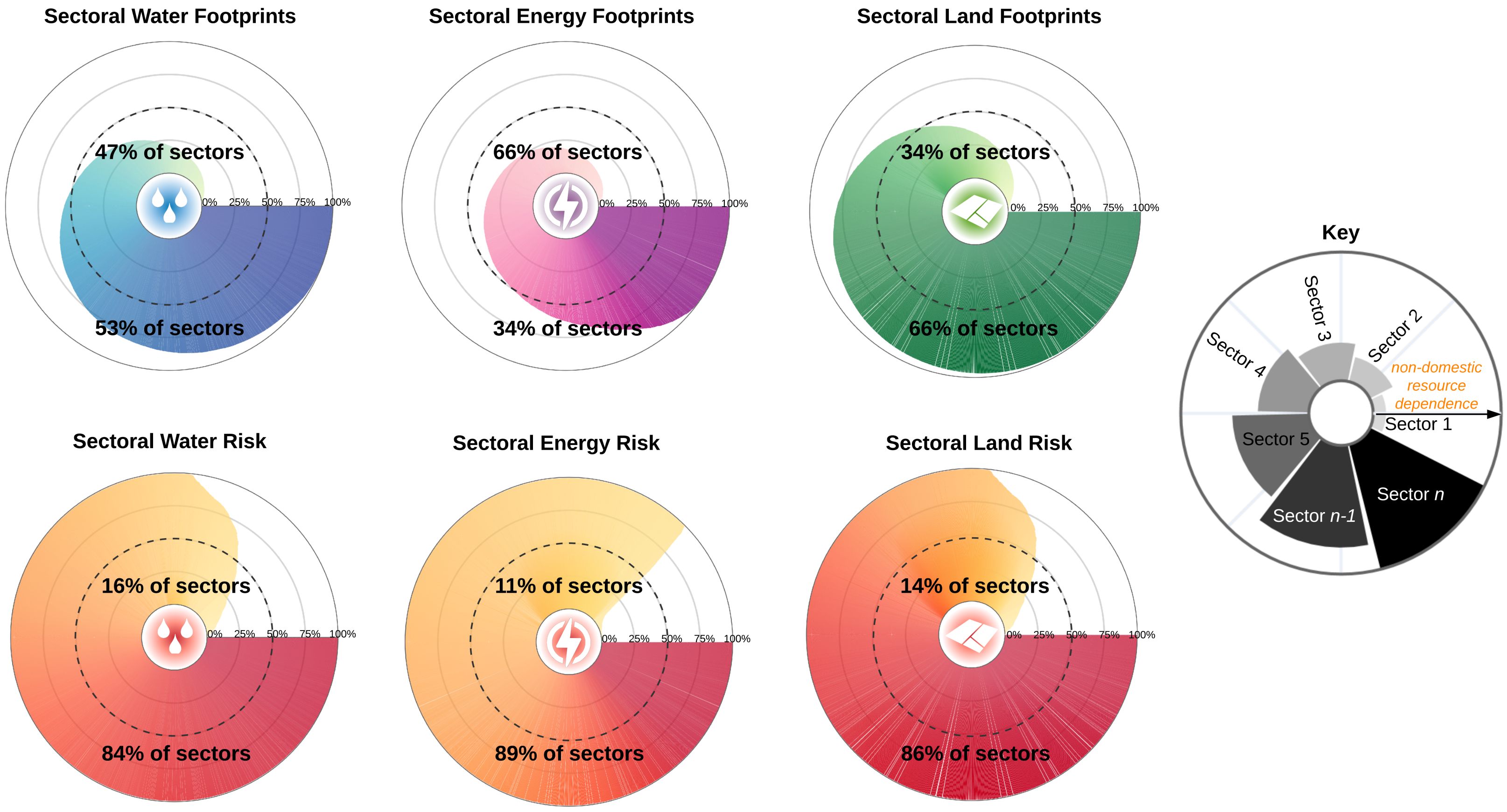

Fig. 4.6 Contribution of trade to sectoral resource use and to high risk resource use
Circular radar graphs displaying the contribution (%) of non-domestic resources (i.e. international trade) to a sector's overall water, energy and land use (top) and high-risk water, energy and land use (bottom). Dashed line delineates the proportion of sectors which exhibit greater reliance on domestic (inside) or non-domestic (outside) resource use or resource risk.

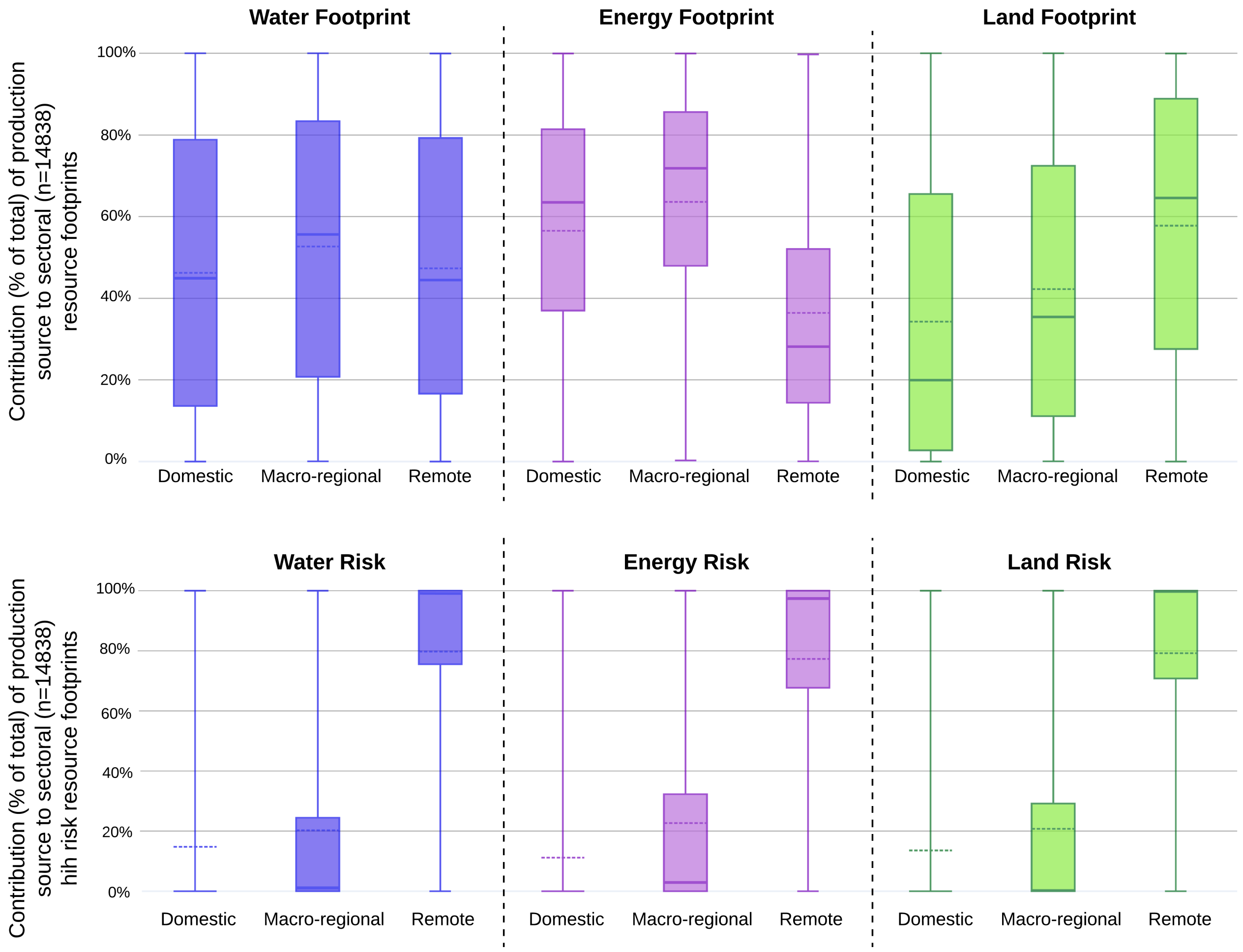

Fig. 4.7 Trade and the WEL footprint of sectors

Box plots showing the contribution of domestic, macro-regional and remote production sources to overall sectoral water, energy and land use (top) and high-risk sectoral water, energy and land use.

The apparent mismatch between spatial scales of national resource dependency and resource risk exposure are of major consequence to resource use assessment in individual countries and globally. Argentina exemplifies this heterogeneity with its most important scales of national exposure to water risk (remote), energy risk (macro-regional) and land risk (domestic) being entirely misaligned. According to this assessment there are no countries for which truncation of WEL system assessment to a national-level or a macro-regional level would capture the most significant source of water, energy and land risk simultaneously.

Ostensibly, the globalised nature of the country and sector interactions across the WEL system implies no obvious entry point to mitigate country and sectoral resource pressures and risks. However, cross-cutting analysis of national and sectoral resource origins across the WEL system, summarised in Figure 4.8, reveals specific regions and countries which exert major influence across this system. To this end, many countries and sectors share the same source of resource supply and risk (Figure 4.8). For all 189 countries analysed, India was one of the greatest sources of national high risk water, followed by Pakistan, Spain and Italy. Thailand is the most common source of national energy risk, a finding supported by other similar studies (see GEI, 2018; Kamsamrong & Sorapipatana, 2014; Vivoda, 2010), followed by Algeria and Ethiopia. The USA, Argentina and Brazil were the top ten sources of land risk. Meanwhile, common sources of national water, energy and land risk also featured among the top sources of sectoral risk, as shown by comparing Figures 4.7 and 4.8. In terms of overall water, energy and land use, the USA, China and Algeria were among the top sources of sectoral resource use (Figure 4.8). The primacy of Algeria to sectoral water, energy and land use is likely explained by its exports of i) oil and gas reserves (in the case of energy), (ii) agricultural commodities produced with low water efficiency and a high ratio of blue to green water (in the case of water) (Jacobs & van Klooster, 2012), and extensive, inefficient land use (in the case of land) (Houyou et al., 2016). The immediate policy implication of the identification of resource risk hot-spots is to divert national procurement away from high risk resource use in key sectors, namely, the food sector in the case of water and land risk and energy-intensive sectors (e.g. construction, transport and infrastructure) in the case of energy risk. However, since such measures might be regressive in nature and difficult to implement in practice, policies to reduce international inequalities and fragility in resource insecure nations should also be explored alongside this. These supply-side measures could involve debt cancellation, investment in resource efficiencies in key sectors, and promotion of equitable and sustainable terms of trade between nations.

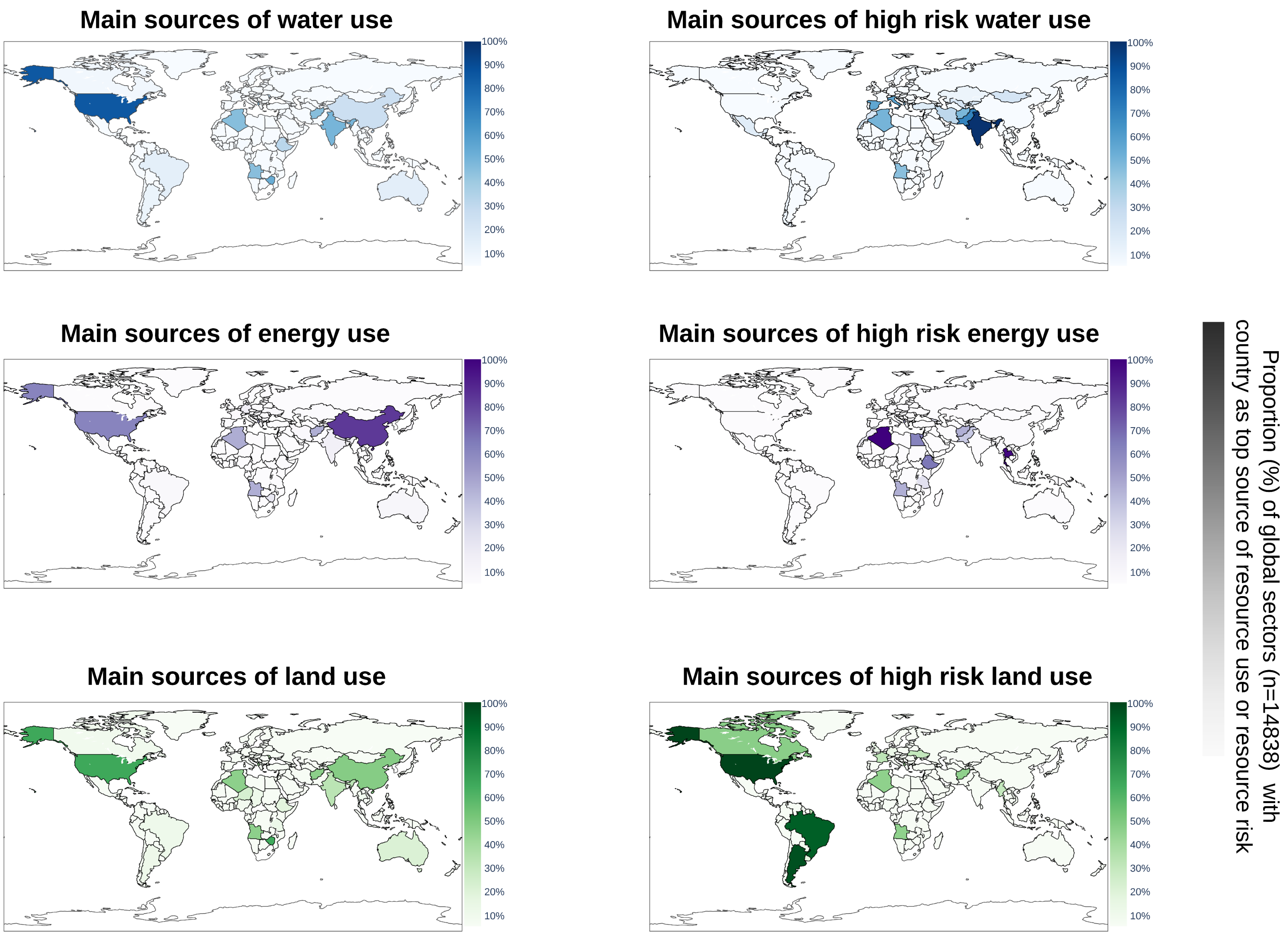

Fig. 4.8 Main sources of resource use and resource risk

Choropleth maps with shading of countries according to their frequency of appearance in the top 10 sources of sectoral resource dependence (left) or high risk sectoral resource dependence (right).

4.3.3 The spatial extent of the UK's water, energy and land footprint

The United Kingdom (UK) is here used as an illustrative case study given its high exposure to and influence on water, energy and land use within global supply chains (Owen et al., 2018). Indeed, in recent years the UK government has expressed an increased interest in analysis of these impacts in order to manage its food security (Sutherland et al., 2013), energy security (Watson et al., 2018), and commitments to international targets in international agreements (West et al., 2016). Since the assessment of water, energy and land resource risks in this chapter follow the same analytical procedure, only the UK's risk and spatial profile of the UK's water footprint is explained in detail here.

In 2015, the UK imposed a global water footprint of 96.86Gm^3 according to this assessment. Although instructive, this information does not distinguish the UK's source of production (domestic or otherwise) and associated resource risk (high, medium or low). As such it provides a blunt tool for guiding the UK's approach to mitigating water risk. Moreover, such an aggregate indicator does not enable meaningful comparison between countries with a similar water footprint to the UK, such as Iran (98Gm^3) and Italy (95.5Gm^3), whose source of water and associated resource risk are entirely unique. Further interrogation of the UK's water footprint, by source and level of risk, reveals further information that could be used to manage and reduce its exposure to and influence on water risk. Figure 4.9 presents the data; key insights which emerge from such an assessment are:

- 80% of the UK's water footprint is imposed outside of its borders;
- Over half of the water used to satisfy UK consumption is met by medium risk water use; and
- UK exposure to high risk water use is mainly transmitted through international trade pathways, but it is also exposed domestically to medium water risk.

In contrast to an aggregate indicator, a decomposed analysis of the UK's water footprint by risk and source locates the actors of critical importance to UK water security. The USA, India, Nigeria, France and China are shown as the UK's main non-domestic sources of water to the UK, whereas India, Spain, Pakistan and Morocco are the main sources of high risk water to the UK.

A similar decomposition of the UK's main sources of energy and land use and risk is presented alongside the the UK's water footprint analysis in Figures 4.10 and 4.10.

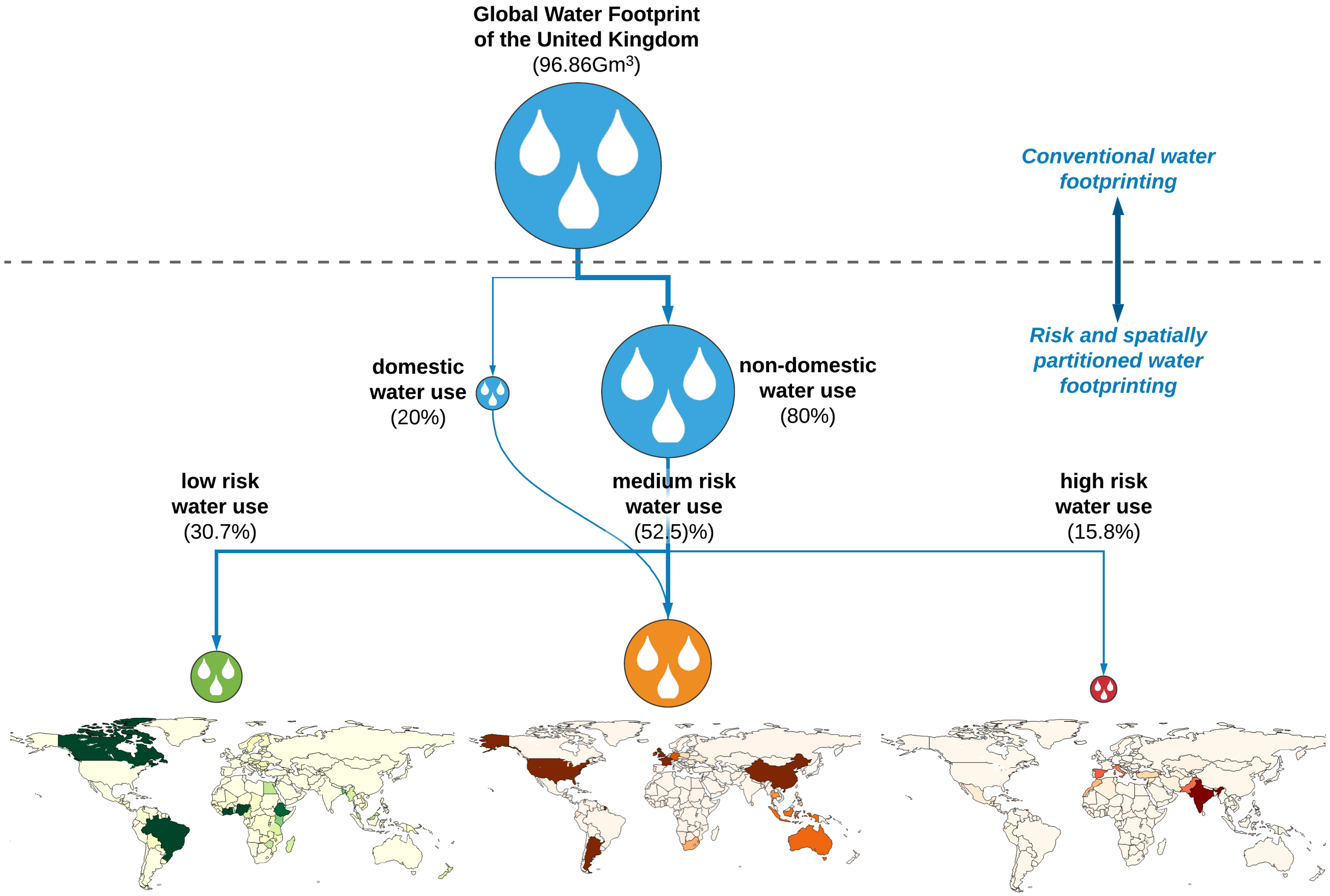

Fig. 4.9 Spatial and risk assessment of the UK's global water footprint

Schematic illustrating a disaggregation of the UK's global water footprint using information on its sources of water use and their associated level of risk across 189 countries.

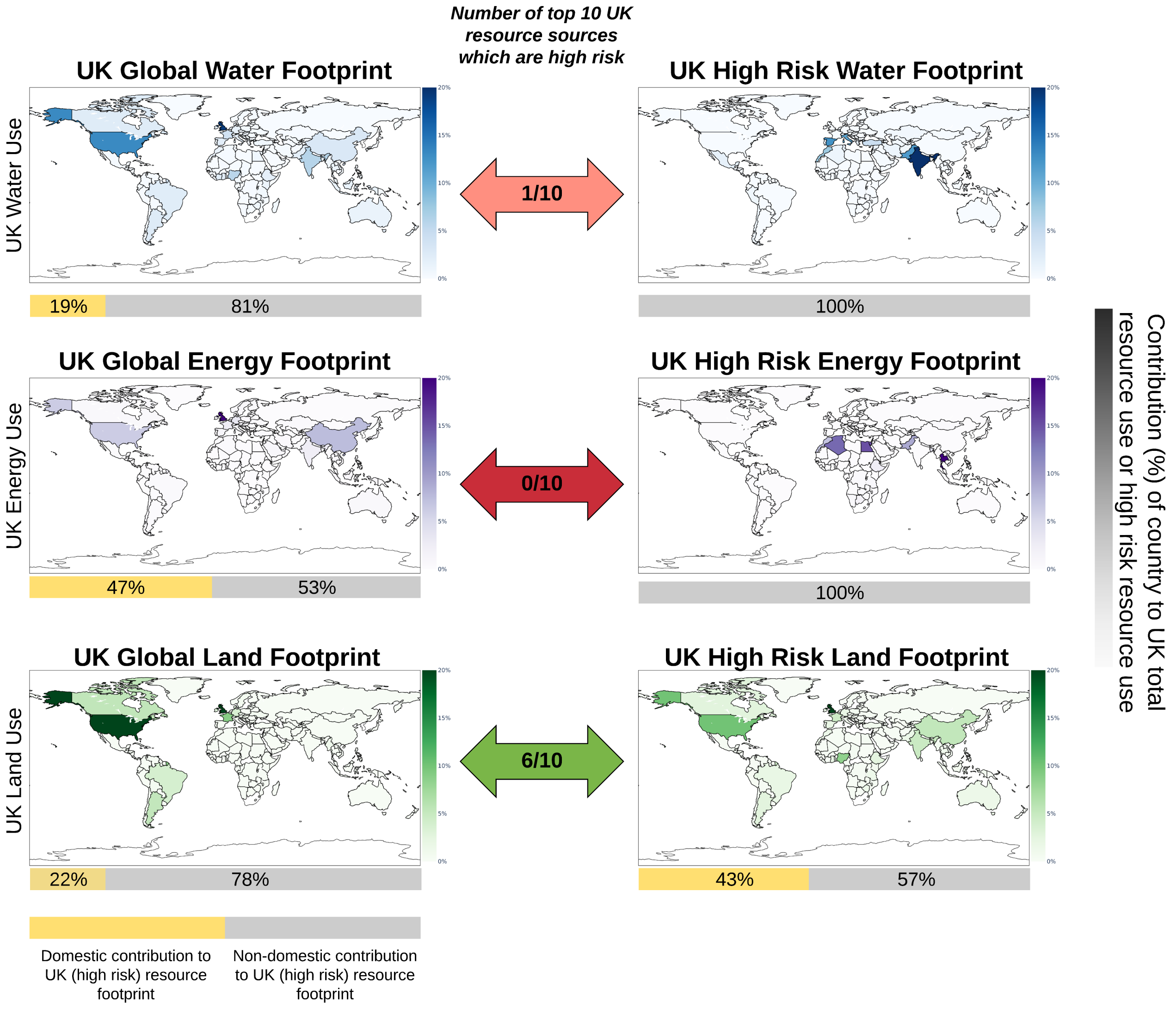

Fig. 4.10 UK sources of resource use and resource risk

Choropleth maps with shading of countries according to their contribution to the UK's overall water, energy and land footprint (left) and high-risk resource use (right), including the proportion of domestic (yellow) and non-domestic (grey) dependence in each case. Bridging arrows between maps illustrate the extent of overlap between the UK's main (top 10) sources of resource supply and risk for each resource use category (water, energy and land).

This overview of the UK's water, energy and land footprint highlights several features of the country's resource security. The UK exhibits low self-sufficiency in water resources (19%) and land resource resources (22%) and relies on countries in remote locations for both these resources. This contrasts with the UK's energy use which is met equally by both domestic and non-domestic sources (Figure 4.10). The profiles of water, energy and land resource risk vary for the UK. Half of the UK's land use is from high risk land sources; this is likely due to its own land use being classified as high risk, which is evidenced by recent concerns over the quality and management of UK agricultural soil (Harvey, 2018). Conversely, the UK exhibits relatively low dependence (15.8%) on high risk water sources and negligible (2%) dependence on high risk energy sources. Within this context, the UK is exclusively exposed to high risk water and energy use from non-domestic sources. However, 45% of the UK's high risk land use is domestic. Poor alignment is found between UK's main sources of resource use and resource risk in relation to water and energy, but its main sources of land use and high risk land use exhibit modest correlation (Figure 4.10). Chapter 5 identifies the sectors pertinent to national water, energy and land pressures and develops, in Section 5.5, the UK case study to this end. These insights for the UK are replicable across the 189 countries and the 14838 sectors analysed and can be used to support case study analysis of a similar scope within these different national and sectoral contexts. The data for developing such case studies is available at Taherzadeh (2020).

4.4 Discussion

The production and consumption of goods and services links economic actors in complex and globalised supply chains. As a result, the environmental burdens of countries and sectors are distributed across various production locations worldwide. Where this resource demand is imposed matters to the effective management of the water-energy-land (WEL) system. However, to date nexus assessment has been truncated, spatially and sectorally, to prevent such a systematic overview of resource pressures and their source. This chapter develops and demonstrates a flexible approach to examining pressures across the WEL system at various spatial and sectoral scales. This framework provides several improvements when compared to existing methods of nexus-based assessment. Undertaking nexus assessment using MRIOA enables a self-consistent cross-comparison of country and sectoral resource pressures across the WEL system. This systematic overview of the WEL system lends itself to the identification of key priorities (countries, regions and sectors) to improve the sustainability of natural resource use in individual countries and globally. The data-driven nature of MRIOA, when used in combination with large environmental datasets, enables rapid development of nexus case studies for a vast number of countries and sectors which would be prohibitively complex and slow using existing nexus-based assessment models and tools (Vivanco et al., 2018a).

By linking country and sector resource use to source, this chapter makes several contributions to nexus scholarship. Foremost, this assessment develops a foundational understanding of country and sectors resource interdependencies across the water-energy-land nexus at national, regional and remote scales. This multi-scale analysis reveals resource pressures and resource risks are often remote from the locations of national and sectoral consumption. This finding has major implications for the study and management of the WEL system, namely, it highlights the need for global-level assessment of country and sector pressures and policy priorities across the WEL system, which is scarcely undertaken at present. This also suggests analysts and decision makers would benefit from exercising caution when truncating nexus-based assessment to national or regional levels since such units of analysis are likely to ignore large, and potentially more significant, resource use and risk driven by countries and sectors via remote international trade flows. Consequently, this assessment provides a strong case for extending national resource management beyond national borders, improving engagement and dialogue amongst actors in global supply chains, and developing appropriate governance frameworks which reflect the transboundary nature of resource risk.

Despite the complex and globalised nature of resource use pathways within the global economy, countries and sectors depend on and are exposed to common sources of resource supply and high risk resource use. This implies that simply diversifying trading partners, is unlikely to help countries and sectors improve their resource self-sufficiency or exposure to resource risks. Accordingly, focusing on resource risk reduction at source appears necessary to promote more sustainable management of water, energy, and land resources, in individual countries and globally. Moreover, within the context of national resource security, reducing dependence on non-domestic resource supply sources, may help to improve the resilience of countries to supply chain shocks related to resource mismanagement upstream in global supply chains.

In addition to its application to nexus-based assessment and management, this chapter contributes towards several other avenues of research and policy inquiry. First, this assessment enables a comparison of different resource insecurities within and between countries and sectors. Second, this detailed decomposition of global water, energy and land use provides a framework and dataset to help operationalise the assessment of risks across their respective planetary boundaries at a national and sectoral level, building on current assessments which utilise conventional footprinting techniques (*cf* Fang et al., 2015; Hoekstra & Wiedmann, 2014; O'Neill et al., 2018). Lastly, this analysis reveals how and where countries outsource water, energy and land risk through their various consumption activities, adding to the body of evidence concerning carbon leakage, virtual resource trade and pollution havens (Bruckner et al., 2012; López et al., 2018; Xu et al., 2019)

These findings must be viewed within the constraints of available data and modelling techniques, discussed in detail in Chapter 3, but recapitulated here for completeness. First, the availability of, and access to, natural resources varies spatially and sectorally. This heterogeneity is not captured using national-level data. Although sub-national resource risk datasets exist for water use (Hoekstra et al., 2012), energy use (BEIS, 2018), and land use (Croft et al., 2018), the absence of detailed sub-national macroeconomic (production, consumption and trade) data precludes analysis of country and sector (risk-based) resource footprints at a higher resolution (Hubacek & Feng, 2016; Otto et al., 2015). Second, grouping country production sources and resource footprints by three risk categories does not fully reflect the severity of risks associated with production sources underpinning national and sectoral consumption. Nevertheless, this ranking offers a reasonable proxy which can be communicated in an accessible and actionable way. Third, the risk indices themselves also introduce uncertainty to this assessment. Risk indices are based on data and modelled outputs which are subject to deficiencies and their relationship to the actual consequences of national exposure to the production sources they measure is potentially complex. This limitation is most pertinent to the energy risk indicator used, which conflates political and environmental threats. However, there is the potential disaggregate composite indices and evaluate the different risks they embodied using the methodological approached developed in this chapter.

Fourth, there is a strong positive, and likely causal, relationship between the severity of country's domestic resource risks and a country's exports. However, it is difficult to unpick an exact cause-effect relationship between domestic resource risk and trade in the absence of time-series data on national resource risks. As such, additional analysis is needed to distinguish the influence of domestic production and export on national resource risk. Fifth, there are known inadequacies of MRIO databases, national environmental accounts and data analysis which could not feasibly be resolved within this thesis research. These mainly concern: the use of financial data instead of physical data to approximate the weight and direction of resource fluxes across global supply chains (Hubacek & Feng, 2016); misreporting and miscalculation of national economic and environmental accounts (Timmer et al., 2015); and, procedures used to ensure input-output tables balance (Lenzen et al., 2013b).

Although limited by the quality of existing data, the flexibility of this assessment framework is capable of accommodating higher resolution national (e.g. municipalities) and sectoral (i.e. firms) forms of nexus assessment, different environmental risk parameters, and expanding definitions of the 'nexus' (e.g. climate, minerals, and/or ecosystems), as new datasets and methods for resource footprinting emerge. To this end, this approach can help to respond to the complex and constantly evolving challenges and questions surrounding global, integrated environmental management.

Chapter 5

Sectoral drivers of the global water-energy-land system

Our present situation is so complex and is so much a reflection of man's multiple activities

Club of Rome, 1972

5.1 Introduction

Effective management of the Water-Energy-Food (WEF) nexus has emerged as the primary objective of natural resource management (Allouche et al., 2015). Ostensibly, this attention on the food system appears warranted. Globally, the food sector accounts for the bulk of water and land use (Bajželj et al., 2014; Hoekstra et al., 2012). The mechanisation of agricultural production and growing irrigation demands has also strengthened dependencies between the food and energy system (Perry & Steduto, 2017). However, natural resources are heavily utilised across other sectors of the economy. Hence, solely focusing on the resource burden of food sectors might overlook other, potentially more important, pathways of resource use.

Although only a sub-system of the so-called water-energy-land (WEL) system (see Figure 1.1 in Chapter 1), the WEF nexus is frequently treated as its equivalent, resulting in a perception of the food sector as all encompassing of water, energy and land use pathways (Allan et al., 2015). Such a conflation means WEF-centric analysis assigns primary importance to the food sector as the most acute pressure on the WEL system. Suggestions of a 'perfect storm' between food demand and resource availability (Beddington, 2009), a 'trilemma' connecting water, energy and food supply (Harvey, 2014), and a 'wicked problem' facing food futures (Kirschke et al., 2018), reinforce this. However, the relative importance of the food sector within the wider context of other drivers of water, energy and land use is poorly understood owing to the narrow sectoral focus of nexus assessment (Taherzadeh et al., 2018).

Studies of non-food sectors highlight the potential importance of extending WEL nexus assessment to encompass multiple economic sectors. Within the context of water use, a review of pressures on the global water system by Hoekstra (2017) has highlighted the significant water use embodied in construction, textiles, electronic equipment, paper and services, whilst noting the need for further study of their impacts. National and global assessments of the energy system chiefly implicate non-food sectors, such as electricity and heat production, buildings, transport and industry (Cullen & Allwood, 2010; IPCC, 2014; Krausmann et al., 2018). Meanwhile, a review by Bruckner et al. (2015) highlights the growing burden of non-food sectors on land resources, including biofuels, oilseeds, fibre crops, textiles and animal hides for leather products. The same review found non-food cropland demand accounted for over 50% of the EU's land use. In addition to cross-sectoral analysis, nexus assessment would also benefit from more detailed assessment of sub-sectors within the food system due to the vast intra-sectoral differences between the resource burden of food products. For example, animal products have emerged as an important driver of water (Gerbens-Leenes et al., 2013; Hoekstra et al., 2012; Schlink et al., 2010), energy (Poore & Nemecek, 2018; Sandström et al., 2018; Smetana et al., 2015) and land impacts (Alexander et al., 2017; Bajželj et al., 2014; Henders et al., 2015; Taherzadeh & Caro, 2019) but are rarely distinguished within the concept or assessment of the so-called 'WEF nexus'.

To better understand the importance of food and other sectors to the WEL system, this chapter evaluates the contribution of different sectors to the resource footprint and risk of national consumption across 189 countries.

By developing a multi-sectoral assessment of the global water, energy and land use pathways, this chapter examines:

1. sectoral drivers of national resource dependency and risk across the WEL system;
2. top sectoral priorities for WEL nexus management in individual countries and globally; and
3. implications of sectoral and spatial boundary setting for WEL nexus assessment.

This chapter begins by outlining key blindspots in the understanding of multi-sectoral impacts across the global the WEL system. Section 5.3 outlines how these knowledge gaps are systematically addressed using the analytical procedures discussed in the preceding chapter (see Section 4.2.3). The findings of this analysis, reported in Section 5.4, examines the above focus areas and further develops the UK case study featured in Chapter 4 (Section 4.3.3) by identifying the UK's sectoral priorities for management of dependencies and risks across the WEL system. Section 5.6 comments on the significance and limitations of these findings and their implications for future research on and management of the global WEL system.

5.2 Tracing sectoral pressures across the WEL system

Insights from studies of the WEL system are highly prescriptive in their application to natural resource management. Nexus scholarship is foremost a policy-driven research agenda (Weitz et al., 2017). The applied nature of nexus research demands interrogation of how recommendations from nexus analysis arise and whether they reflect systemic policy priorities. In Chapter 4, the importance of spatial scales for nexus assessment was examined.

However, the scale-bias of nexus analysis is merely a feature of current scholarship and not a guiding principle. In contrast, WEF-centric nexus assessment assigns central importance to food supply as a driver of water, energy and land use, as evidence by recent reviews of nexus scholarship (*cf* Endo et al., 2015; Galaitsi et al., 2018; Green et al., 2016; Leck et al., 2015; Liu et al., 2015; Simpson & Jewitt, 2019; Wichelns, 2017). In a similar vein to the spatial partitioning of country resource footprints to reveal their cross-scale dependencies, it is necessary to partition country resource footprints sectorally to reveal sectoral drivers of water, energy and land use.

The environmental impacts of different economic sectors have been exhaustively studied, over several decades. Despite the plethora of empirical analysis of sector assessment, few studies possess the cross-sectoral and multi-dimensional qualities needed to meaningfully assess sectoral priorities for effective national management of combined water-energy-land pressures. Although highly instructive, recent studies in this direction have been limited to (i) global-scale sectoral priority assessment (*cf* Howells et al., 2013; Vivanco et al., 2018a; Xu et al., 2019), (ii) single country or region analysis (*cf* Bijl et al., 2018; Munoz Castillo et al., 2019; White et al., 2018), and (iii) partial analysis of the WEL system (e.g. water-energy, energy-land, or water-land) (*cf* Duan & Chen, 2017; Kirschke et al., 2018; Vivanco et al., 2018b).

Several perspectives of resource use are needed to establish the importance of food and other economic sectors within the context of national water, energy and land footprints. This chapter identifies and develops three lines of inquiry. First, the contribution of food sectors to pathways of national resource use and associated risk across the WEL system are evaluated by cross-sectoral analysis of country water, energy and land footprints. Second, assessment of country water, energy and land footprints is used to determine whether food-related sectors represent the main source of national resource use and associated risk across the WEL system. This evaluation also reveals the potential for a triage-based approach to managing major pressures across the WEL system through the targeting of interventions in a small number of sectors. Lastly, these insights are combined with spatial boundary analysis of country resource footprints, as developed in Chapter 4, to assess the implications of truncating nexus-based assessment sectorally and spatially.

5.3 Methods

The sector-level assessment of resource dependencies and risk exposure featured in this chapter employs the same analytical framework, data and modelling principles introduced in Chapter 4. As such, only the additional procedures for analysis in this chapter are discussed here. The main requirement for evaluating the contribution and significance of food sectors to global and national water, energy and land use involved identifying food-related sectors within the Eora (2019) MRIO database. Due to the different resolution of national economic accounts - ranging from 26 sectors to 1022 sectors, the disaggregation of food-related sectors varies between country. Countries (n = 120) with 26 sectors had only a primary and secondary sector associated with food: "Agriculture" and "Food and Beverages". However, the national accounts for major, developed economies included a larger, more detailed range of food-related sectors with commodity- and product-level detail (e.g. cattle raising, wheat production, and live fish).

Economic sectors were classified with an eye to capturing the entire ‘food economy’ and non-food economy in both individual countries and globally. This included sectors associated with food production (e.g. crop cultivation, livestock farming, and aquaculture), food and drink processing and manufacture (e.g. milling, cheese making, and confectionary), and places of food and drink consumption (e.g. restaurants and bars). Although WEF-centric analysis tends only to focus on water, energy and land use associated with food production, a broader categorisation enabled (i) identification of upstream drivers of agricultural production (e.g. fertilser usage, machinery, and transport), (ii) delineation of non-food drivers of agricultural production (e.g. textiles, apparel and bioenergy), and (iii) assessment of the full potential of WEL nexus assessment within a food systems context. Where sector categorisation in national accounts combined several sectors (e.g. "Agriculture, hunting, Forestry and Fishing"), they were grouped according to the proportion of food or non-food terms in sector descriptions which in most cases was clear. The use of consumption-based resource accounting also meant that non-food sectors which produce inputs to the food system (e.g. energy for the fertiliser sector, machinery, or agricultural service support) were captured in the assessment of food-related resource use and associated risk. In total, 2123 sectors were categorised as food related which represents just over one-fifth of the sectors in the Eora (2019) database. At a country level this ranged from two sectors to 189 sectors (in the UK) with an average of 11 food-related sectors per country.

5.4 Analysis

The significance of the food economy to water, energy and land use pathways is evaluated in three parts. Section 5.4.1 evaluates the contribution of food-related sectors to national resource footprints and risk across the global WEL system. Section 5.4.2 examines whether food-related sectors constituent the principal source of resource use and associated risk in relation to national water, energy and land footprints. Lastly, Section 5.4.3 explores dual effects of sectoral and spatial boundary setting in relation to nexus-based assessment.

5.4.1 Food system interactions across the WEL system

The contribution of food-related sectors to global water, energy and land footprints has remained relatively constant in recent time, as shown in Figure 5.1. Unsurprisingly, the global food economy is responsible for the majority of global water use (67.2%) and land use (72.6%). In contrast, the energy footprint of the food economy is relatively small (9.3%) when viewed within the context of the wider energy burden of global economic activity.

Country-level resource footprinting of sectors reveals a large variation in the contribution of the food economy to national water, energy and land footprints (Figure 5.2). In line with the global picture, food-related sectors still account for the majority of water use (median = 61.5%, mean = 60.26%) and land use (median = 62.7%, mean = 61.2%) in most country contexts. Indeed, food-related sectors contribute to over 50% of national water and land footprints in 139 of the 189 countries modelled. Although significant, food-related sectors are not the only contributor to countries' water and land footprints. Consumption from food-related sectors represents the principal (>90%) driver of water and land footprints in only three countries: Vietnam, the Philippines and Kyrgyzstan. Moreover, large national variation is observable in the contribution of food-related sectors to national water footprints (8.7%-94.3%) and land footprints (14.6%-95.8%) implying cross-country differences in the importance of WEF-centric analyis. In terms of the energy system, food-related sectors make only a modest contribution (median = 6.6%, mean = 7.5%) to the overall energy footprint of countries. In 155 countries, consumption across food-related sectors was responsible for less than 10% of the their total global energy footprint.

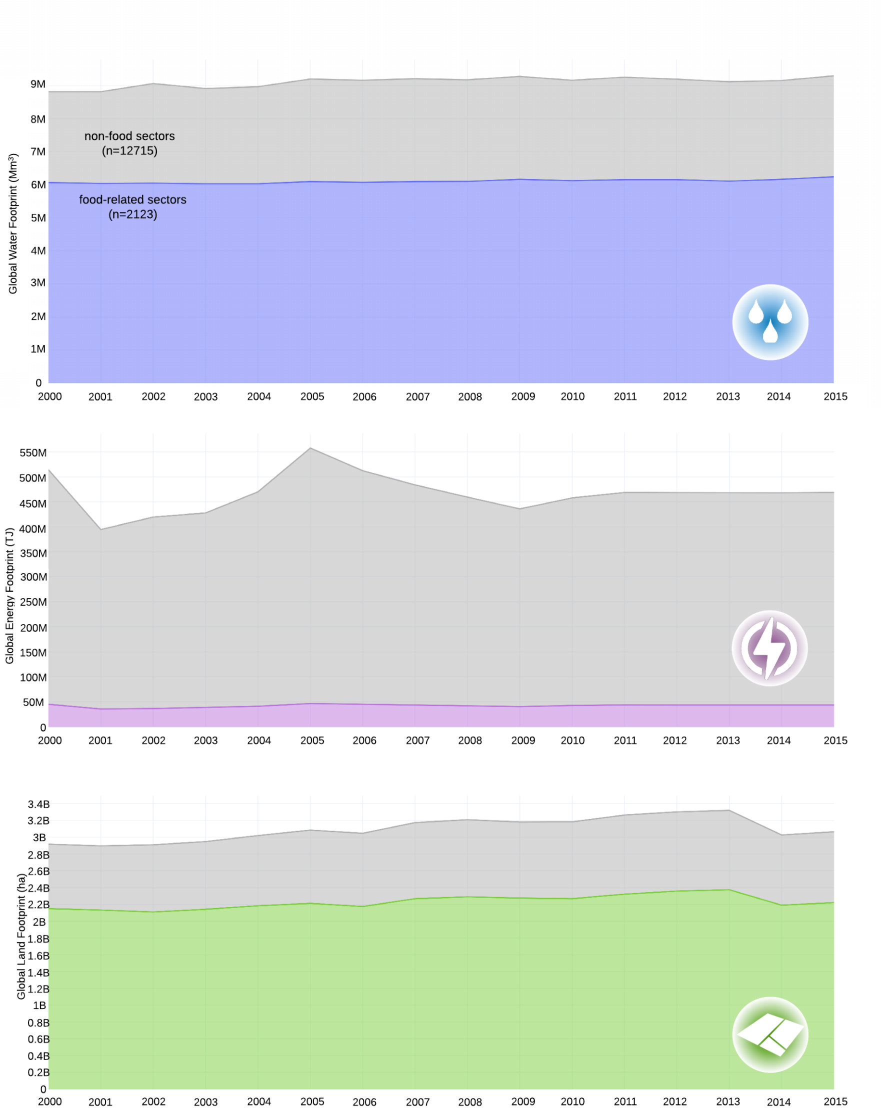

Fig. 5.1 Contribution of food and other sectors to global resource footprints

Graphs showing the contribution of food-related sectors (coloured) and non-food sectors (grey) to the water, energy and land footprint of global consumption between 2000 and 2015.

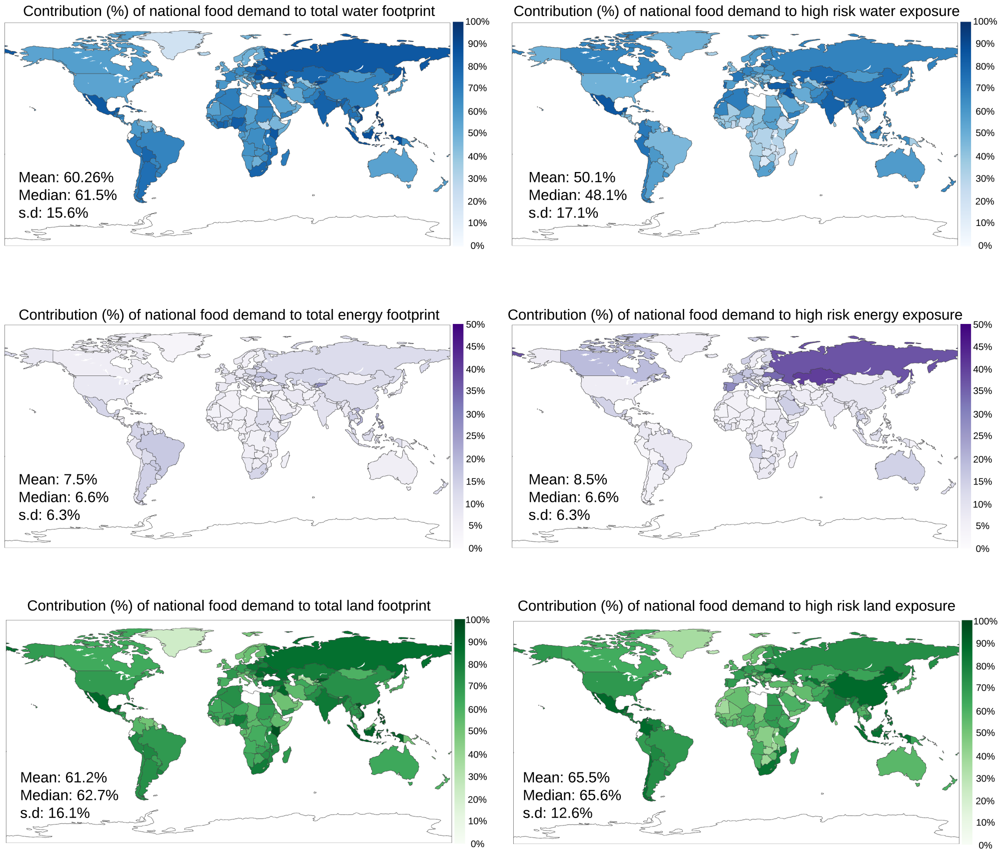

Fig. 5.2 Contribution of food sectors to national resource footprints and risk

Choropleth maps showing the contribution of consumption from food-related sectors to national water, energy and land footprints (left) and national high risk water, energy and land use. Mean, median and standard deviation (s.d.) values convey the distribution of values within each analysis.

Since priorities across the WEL system might also be directed by concerns of resource insecurity, it is important to consider the significance of the food economy within the context of high risk water, energy and land use. Food-related sectors are responsible for 72.3% of the global high risk water use, as well as 8.5% of global high risk energy use, and 70.3% of global high risk land use. However, when viewed within the context of national resource risk, food-related sectors were a less significant driver of exposure to high risk water use (median = 48.1%, mean = 50.1%) and high risk land use (median = 65.6%, mean = 65.5%). In parallel with the global picture, food-related sectors contribute modestly (median = 6.6%, mean = 8.5%) to national exposure to high risk energy use (see Figure 5.2).

Studying how national food demand drives global water, energy and land use reveals country contexts where WEF-centric analysis is likely to be most and least effective at identifying critical priorities for integrated management of the WEL system. The propensity of WEF-centric analysis to highlight critical priorities for managing the WEL system relies on the food economy being the sole influence of resource demand and risk in relation to water, energy and land systems, which is not evident from a cross-sectoral analysis of national and global resource use pathways. However, such an aggregate assessment does not establish whether food-related sectors are the principal driver of national influence across the WEL system. In order to determine whether food sectors should be afforded priority within national nexus-based management a triage-based assessment which ranks the influence of sectors to the resource footprint and risk of countries is needed. This is performed in the next Section.

5.4.2 Triage assessment of sectoral pressures on the WEL system

A triage-based assessment of sectoral influence across the WEL system reveals the relative importance of food-related sectors to the water and land footprints of national and global consumption. Nationally, food-related sectors were the main contributor to national water footprints in 176 of the 189 countries analysed. Food-related sectors were also the main contributor to national land footprints in 182 countries. However, national energy footprints were primarily (in 182 countries) driven by demand for non-food sectors. Non-food priority sectors included construction, energy production, textiles, rubber, transport (including infrastructure), and services (e.g. public administration, education, and healthcare). Meanwhile, livestock production, processing or consumption were the main contributing sectors to national water and land footprints in several countries, including Argentina, Bolivia, Denmark, Ecuador, Georgia, Iran, Israel, New Zealand, South Korea, Taiwan, the UK, Uruguay, and Venezuela. Other food-related sub-sectors of importance to country water and land footprints were also flagged, including grain production (USA), rice production (Vietnam, Thailand, and Australia), and grain milling (Indonesia and Kenya). However, the coarse sectoral resolution of national accounts prevented a detailed disaggregation of sub-sectors responsible for country water, energy and land footprints in all cases.

The apparent heterogeneity of key sectors to national resource footprints - most acute in the case of national energy footprints - implies a need to refocus nexus-based assessment on the whole economy instead of single sectors as is currently the case. However, the responsibility of a small number of country sectors for the vast majority of pressures and risks across the WEL system highlights the potential for a triage-based approach to managing pressures across the WEL system. Figure 5.3 illustrates how pressures and risks across the global WEL system is driven by consumption across a small proportion of global sectors. For instance, consumption across 1% of sectors is responsible for over 90% of water, energy and land use within the global economy and over 80% of high risk water, energy and land use. The top sectors contributing to overall global water, energy and land use and high risk water, energy and land use are summarised in Table 5.1 and Table 5.2 respectively.

Sectors within the USA, China, India and Russia appear most frequently among the top contributors to the water, energy and land footprint of global consumption (see Table 5.1). However, the sectoral profile of these key contributors is diverse. Despite the primacy of food-related sectors to global water and land footprints, non-food sectors also exhibit major influence in these domains. According to this analysis, USA cotton farming is the sixth largest contributor to the water footprint of global consumption, with a water footprint of 174.7Gm^3. The water footprint of USA cotton farming is primarily (95.9%) driven by domestic consumption in the USA. Construction in China, also appears among the top 10 contributors to the water *and* land footprint of global consumption, implying a need to extend water-land nexus assessment beyond the food system. This need is most acute when considering the energy footprint of global consumption of which food-related sectors are not a main contributor (Table 5.1). Construction, energy production and supply, and public administration are the top contributing sectors to the energy footprint of global consumption. The high energy footprint associated with public administration is due to its large, final demand for upstream production across a variety of other energy-intensive sectors including energy production and supply, technology, food and construction.

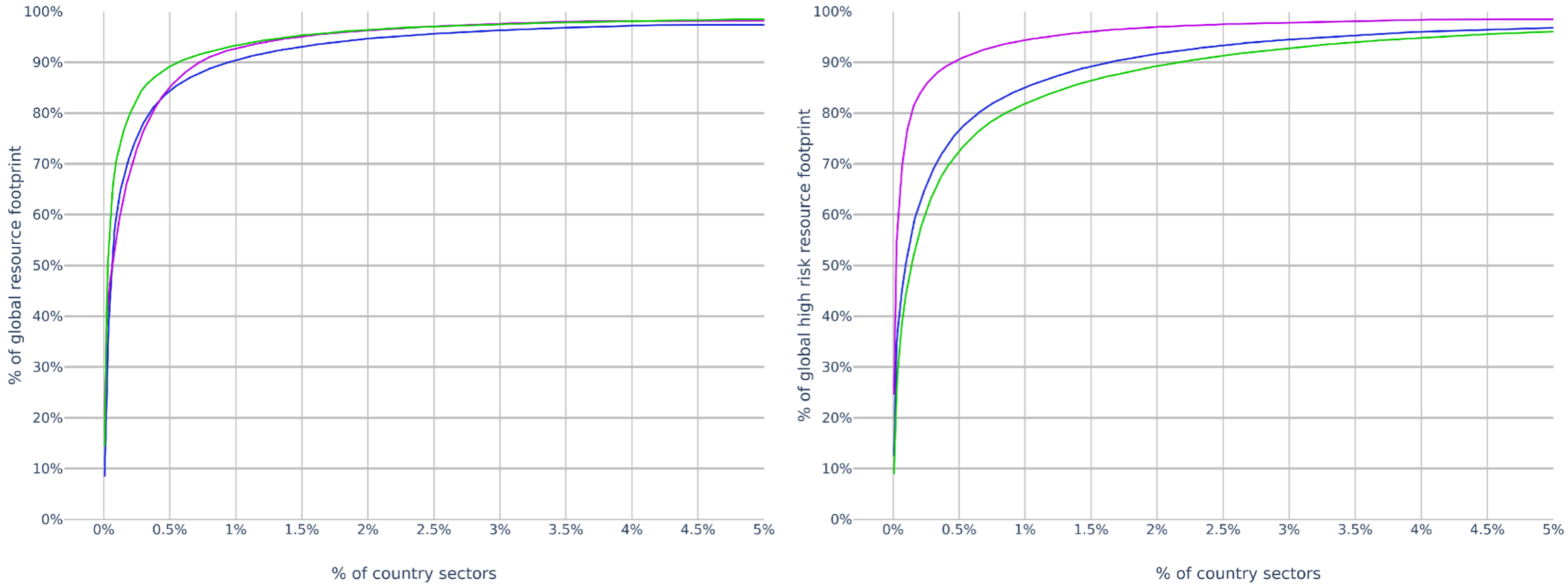

Fig. 5.3 Sectoral concentration of pressures across the WEL system

Cumulative frequency plots showing the contribution of country sectors (% of total, 14838 sectors) to global water, energy and land footprints (left) and global high risk water, energy and land use (right) ranked in descending order. Steeper curves indicate resource pressures are more highly concentrated among a small proportion of country sectors (e.g. Energy risk vs Land risk).

Table 5.1 Top ten sectors by water, energy and land footprint

Top 10 sectors byWater Footprint	**Top 10 sectors by Energy Footprint**	**Top 10 sectors by Land Footprint**
1. USA | Grain farming	1. China | Construction	1. China | Crop cultivation
2. China | Crop cultivation	2. USA | Elec. power gen., trans., and distr.	2. USA | Grain farming
3. India | Paddy	3. USA | State and local government serv.	3. China | Construction
4. USA | Oilseed farming	4. China | Elec. prod. and supply	4. Russia | Agr., hunt., forest., fish.
5. Russia | Agr., hunt., forest., fish.	5. USA | Natural gas distribution	5. India | Paddy
6. USA | Cotton farming	6. China | Industrial equipment	6. India | Wheat
7. India | Other crops	7. China | Public admin. and other	7. China | Livestock + products
8. China | Construction	8. India | Construction	8. India | Other crops
9. Indonesia | Milled grain and flour	9. USA | Retail trade	9. Nigeria | Agriculture
10. China | Livestock and products	10. Russia | Construction	10. Russia | Food, bev. and tobacco

Table 5.2 Top ten sectors by high risk water, energy and land footprint

Top 10 sectors by High Risk Water Footprint	**Top 10 sectors by High Risk Energy Footprint**	**Top 10 sectors by High Risk Land Footprint**
1. India | Paddy	1. Hong Kong | Construction	1. USA | Grain farming
3. India | Misc. food products	3. Egypt | Elec., Gas, Water	3. USA | Animal slaughtering (Excl. poultry)
4. India | Wheat	4. Hong Kong | Trade and transport	4. Ukraine | Agriculture
5. Mexico | Food industry	5. Pakistan | Elec., Gas, Water	5. USA | Poultry processing
6. Pakistan | Food & Beverages	6. Egypt | Transport	6. USA | Food services and drinking places
7. Turkey | Agriculture and hunting	7. Thailand | Railways	7. USA | Frozen food manufacturing
8. Mexico | Agriculture	8. Thailand | Spirits	8. USA | Dog and cat food manufacturing
9. Iran | Meat and meat products	9. Bangladesh | Elec., Gas, Water	9. Brazil | Other product growing
10. India | Hotels and restaurants	10. Pakistan | Transport	10. Germany | Food products

The top sectors contributing to high risk water, energy and land use associated with global consumption implicate a diverse range of countries and sectors. Whilst food production sectors are the dominant driver of global water and land footprints, downstream food sectors appear more influential within the context of high risk water and land use. For example, demand for food manufacturing and food related services in the USA and India appear among the top ten global sources of high risk water and land use. Interestingly, dog and cat food manufacturing in the USA, driven primarily (96.4%) by domestic demand, has the 7th largest high risk land footprint of the sectors analysed. The significance of pet ownership as a driver of natural resource use is evidenced in a recent study by Okin (2017) which found food consumption by cats and dogs constitute about 25–30% of the environmental impacts from animal production in terms of the use of land, water, fossil fuel, phosphate, and biocides. Acknowledgement of the environmental impacts of pet ownership have gained wider attention in recent years, popularising the term 'ecological pawprint' (*cf* Eirini & Tsolakis, 2017; Martens et al., 2019; Su et al., 2018). However, pet ownership is seldom the focus of measures designed to reduce the ecological footprint of humanity, suggesting the need to widen the lens of WEF nexus assessment and management beyond direct human food consumption.

The top sectoral sources of global high risk energy use include a diverse array of sectors, from energy production and supply itself, construction, to trade and transport, apparel, and beverages. Three sectors in Hong Kong - construction, apparel, and trade and transport - feature among the top global sources of high risk energy use. In the case of apparel, demand is driven by consumption in Hong Kong (58.2%), the USA (15.1%), China (6%), the UK (3.52%) and Germany (1.62%).

5.4.3 Boundary setting across the WEL system

Within the context of global environmental footprinting, the effects of boundary setting (i.e. truncating analyses of resource use pathways within a specific system scope) are routinely discussed and investigated within two main contexts, (i) supply chain scope (Feng et al., 2011; Hertwich & Wood, 2018; Suh et al., 2004) and (ii) spatial scale (Cabernard et al., 2019; Chen & Han, 2015; Davis & Caldeira, 2010; Peters, 2008). However, the implications of combined sectoral *and* spatial boundary setting on analyses of national pressures across the WEL system have received less attention.

The contributions of food and non-food sectors to national water, energy and land footprints are evaluated within the context of domestic resource use and international trade. Six system boundaries of assessment were developed:

- **Internal domestic food footprint**: Domestic resource use associated with national final consumption from countries' own food-related sectors

- **Internal domestic other sector footprint**: Domestic resource use associated with national final consumption from countries' own non-food related sectors

- **Global domestic food footprint**: Global resource use associated with national final consumption from countries' own food-related sectors

- **Global domestic other sector footprint**: Global resource use associated with national final consumption from countries' own non-food related sectors

- **Global non-domestic food footprint**: Global resource use associated with national final consumption from other countries' food related sectors (i.e. resource use embodied in country imports from food related sectors)

- **Global non-domestic other sector footprint**: Global resource use associated with national final consumption from other countries' non-food related sectors (i.e. resource use embodied in country imports from non-food related sectors)

These boundaries are intended to capture the scales at which nexus-based assessment is currently undertaken, interrogate the importance of less common boundaries of analysis (such as non-domestic sectors), and provide a heuristically useful evidence base to guide sectoral nexus-based assessment of countries at appropriate scales.

Figure 5.4 illustrates the effects of sectoral and spatial boundaries in relation to national water, energy and land global footprints. The relative importance of sectoral and spatial boundaries of resource footprinting to national resource footprints are influenced by several factors, including (i) the reliance of national sectors on non-domestic resource use, (ii) the dependence of national consumption on non-domestic final output, and (iii) the sectoral profile of national consumption. Despite the variation of these factors between countries, this analysis reveals the limits of truncating nexus assessment spatially and sectorally (Figure 5.4).

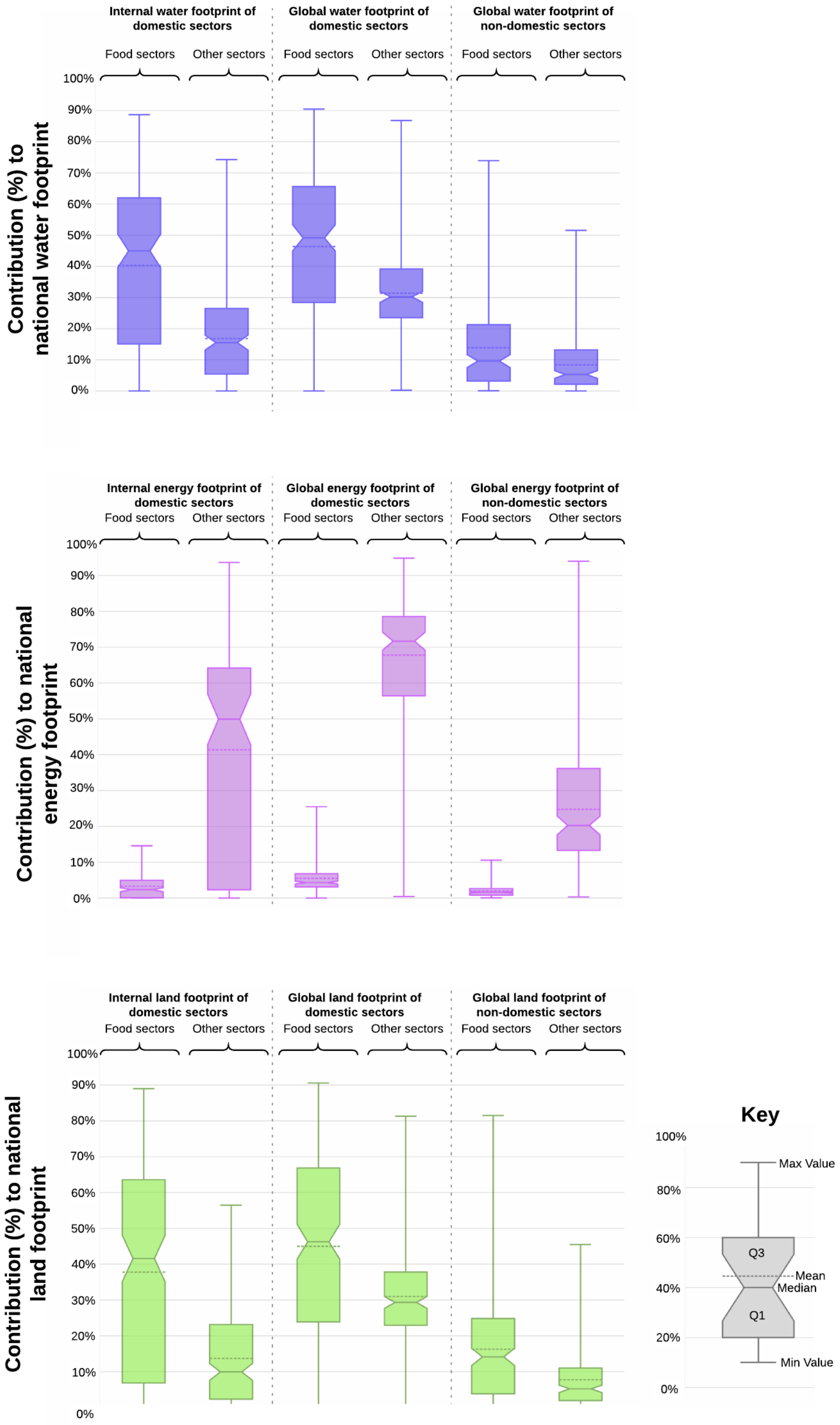

Fig. 5.4 Effects of sectoral and spatial boundary setting on WEL assessment

Box plots showing the contribution of food and other sectors to national water, energy and land footprints (n=189) when evaluated within different resource accounting boundaries.

For food-related resource use the average additional effects of analysing countries' resource footprints within a global context (i.e. capturing virtual/embodied resource use) for water, energy and land footprints is 6%, 2.2% and 7.2% respectively. The equivalent average additional effects of analysing the water, energy and land footprints of countries' non-food related sectors is 14.6%, 26.4% and 17.3% respectively. Moreover, direct national consumption from non-domestic sectors represents an important source of national water (mean = 22.3%), energy (mean = 26.7%) and land (mean = 24%). As such, truncating nexus assessment to domestic sectors omits a potentially large source of countries' water, energy and land footprint, from intermediate production and final goods and services. The remainder of this analysis section examines the priorities arising from sectoral resource footprinting of the UK for nexus assessment.

5.5 Priority sectors for managing UK influence across the WEL system

Continuing from the spatial decomposition of the UK's pressures on water, energy and land resources in Chapter 4 Section 4.3.3, this section highlights their underlying sectoral drivers. To mirror the analysis undertaken at a global scale, this abridged analysis examines (i) the contribution of food and non-food related sectors to the UK's water, energy and land footprint, (ii) the sectoral profile of the UK's top sources of resource use and associated risk across the WEL system, and (iii) the implications of sectoral and spatial boundary setting for studying the UK's water, energy and land footprint. The high sectoral resolution of the UK input-output table in the Eora (2019) database enables a meaningful assessment of the importance of food sectors and associated food system boundary setting in country-level evaluation of priorities across the WEL system. The UK's national economic and environmental accounts cover 1022 sectors of which 189 are food-related sectors. Such granularity of sectoral accounts, including the highest number of food-related sectors of any country within the Eora (2019) database, helps to identify specific consumption activities responsible for the UK's resource footprint.

The contribution of food-related sectors to the UK's global water, energy and land footprint is 52%, 8.8% and 55.2% respectively. The responsibility of food-related sectors to the UK's water and land footprint is lower than the global average, whilst its contribution to the UK's energy footprint is marginally higher. This disparity was more acute when comparing the contribution of food-related sectors to high risk water, energy and land use arising from UK consumption, compared with global consumption. Here, food-related sectors made a less than average contribution to the UK's high risk water use (44.2%), energy use (5.5%) and land use (57.5%) footprint. This high-level analysis suggests an important role of accounting for non-food sectors to assess the UK's water, energy and land impacts. However, whether food-related sectors represent a sensible entry point for management of UK pressures across the WEL system depends on their relative importance among the top sectoral drivers of the UK's water, energy and land footprint.

The top sectors contributing to the UK's water, energy and land footprint and its high risk water, energy and land footprint are presented in Tables 5.3 and 5.4. Food-related sectors appear to dominate the burden of UK consumption in relation to water and land, as well as in relation to high-risk water and land use. UK dairies and cheese making is the top driver of the UK's water and land footprint closely followed by dairy cattle raising and cow milk production, underlining the major importance of consumption of animal products to the UK's environmental footprint. The significance of animal products to the UK's water and land footprint is also evidenced in recent studies of a similar scope (*cf* Hoekstra & Mekonnen, 2016; Owen et al., 2018; de Ruiter et al., 2017; West et al., 2016). Meanwhile, food and beverages from the Netherlands - a major exporting hub of agricultural products (Ercsey-Ravasz et al., 2012) - is also a top contributor to the UK's water and land footprint and the only non-domestic sector of major importance within the context of the pressure UK consumption exerts across water, energy and land resources. No food-related sectors appear among the top sectoral sources of the UK's energy footprint, which includes gas production, electricity distribution, rail transport, hospitals, and public administration.

The main sectoral sources of UK exposure to high risk water implicate food-related sectors of Italy, Belgium, Spain, and India. Consumption from hotels and restaurants in India is also a primary source of the UK's use of high risk water sources arising from tourist consumption activities which is formally classified as domestic consumption (and associated imported virtual resource use) under the UN (2014) System for Economic and Environmental Accounting. The UK's top five sources of high risk land use were all domestic and feature three sectors explicitly related to consumption of animal products: cheese making, cow milk production and poultry production. In contrast to the UK's energy footprint, the top sources of UK high risk energy use were all non-domestic and driven by consumption of clothing, textiles, jewellery and other related items (Table 5.4). Demand for railway services in Thailand was also a source of high risk energy use, due to tourism, so not a material risk to the UK's energy security. Moreover, the significance of these sectors must be viewed within the context of the overall contribution of high risk water use (15.8%) to the UK's water footprint and the overall contribution of high risk energy use (2.4%) to the UK's energy footprint.

The spatial and sectoral diversity of consumption activities responsible for UK influence across water, energy and land resources highlights the importance of careful boundary setting to assess policy priorities for sustainable resource management within this context. Figure 5.5 illustrates the coverage of the aforementioned resource accounting boundaries as applied to the UK's water, energy and land footprint. Truncating accounting of the UK's resource footprint to only the internal (i.e. national) resource footprint of domestic sectors captures less than 20% of its overall water and land footprint and less than 50% of its overall energy footprint. A significant improvement to coverage of these impacts is achieved by accounting for the resource footprint of the UK's domestic consumption within a global context: 37.5% for water, 22% for energy, and 37.8% for land. Furthermore, due to the high reliance of the UK on sectoral output from non-domestic sectors, extending accounting of the UK's resource footprint to these sectors also appears necessary in order to capture more fully the UK's water, energy and land footprint. The contributions of UK demand for final output from non-domestic sectors to the the UK's water, energy and land footprint are 43.4%, 31.1% and 40.5% respectively.

This sectoral decomposition of the UK's water, energy and land footprint suggests WEF-centric analysis of the UK, levelled at a domestic scale, is likely to disguise rather than reveal key opportunities for integrated environmental management of the country's consumption. Particular attention on the UK's dependence on non-domestic sectors, as both sources of production inputs and final goods and services, is necessary for meaningfully management of the pressures of UK consumption on water, energy and land resources. These insights acquired for the UK context are illustrative of the richness of data generated from this chapter's assessment and can be performed for any of the 189 countries studied.

Table 5.3 UK top sources of water, energy and land footprint

Top sectoral sources of UK water footprint	Top sectoral sources of UK energy footprint	Top sectoral sources of UK land footprint
UK | Dairies and cheese making	UK | Man. And dist. of gas	UK | Dairies and cheese making
Netherlands | Food and bev.	UK | Dist. and trade in electricity	UK | Dairy cattle raising + cow milk prod.
UK | Dairy cattle raising + raw milk prod.	UK | Intercity passenger rail transport	Netherlands | Food and bev.
UK | Bars	UK | Hospital activities	UK | Bars
UK | Restaurants	UK | Public administration activities	UK | Restaurants

Table 5.4 UK top sources of high risk water, energy and land use

Top sectoral sources of UK high risk water use	Top sectoral sources of UK high risk energy use	Top sectoral sources of UK high risk land use
Italy | Food and bev.	Hong Kong | wearing apparels	UK | Dairies and cheese making
India | Misc. food products	Thailand | Jewelry & Related Articles	UK | Dairy cattle raising + cow milk prod.
India | Hotels and restaurants	Thailand | Railways	UK | Bars
Belgium | Food and bev.	Pakistan | Textiles and Wearing Apparel	UK | Restaurants
Spain | Other food products	Morocco | Textiles and Wearing Apparel	UK | Farming of poultry

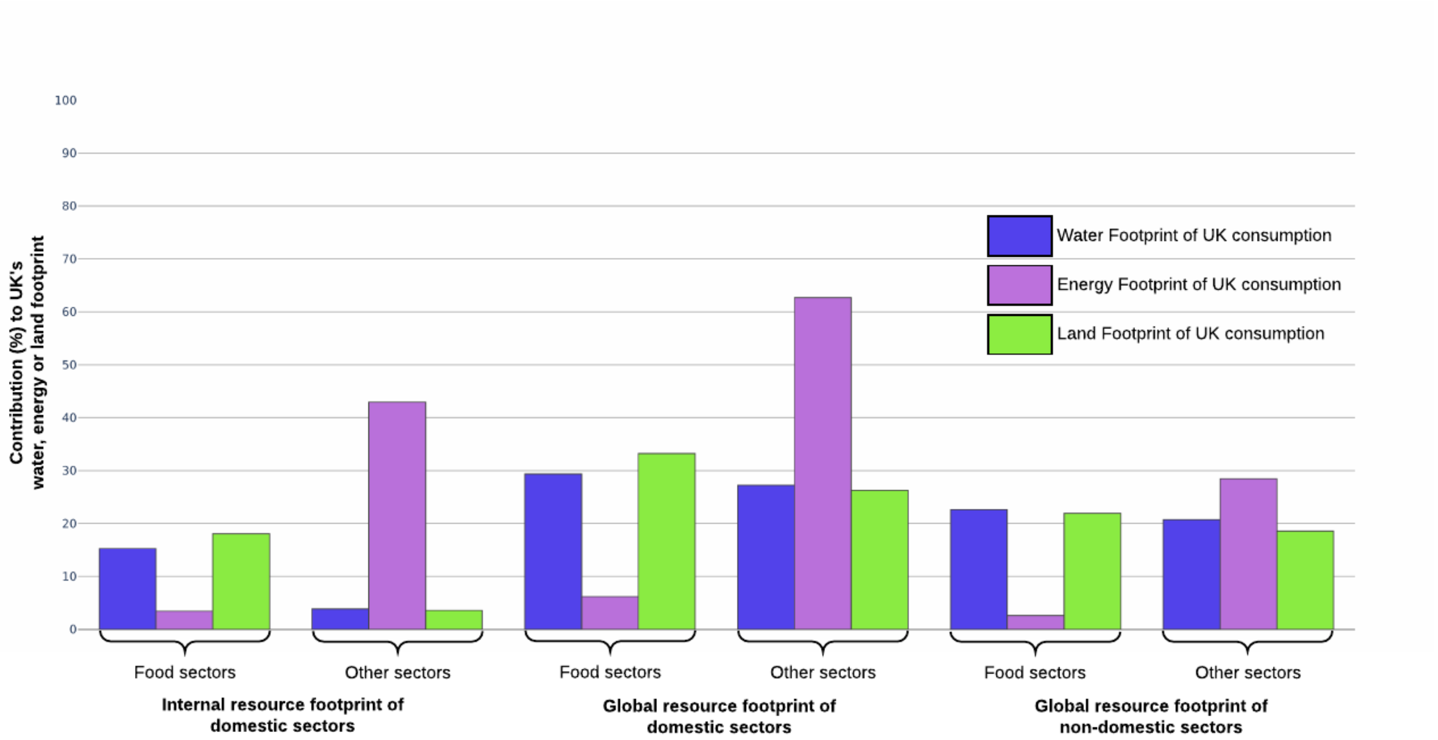

Fig. 5.5 Effects of sectoral and spatial boundaring setting on UK WEL assessment

Plot showing the contribution of food and other sectors to the UK's water, energy and land footprints (n=189) when evaluated within different resource accounting boundaries.

5.6 Discussion

This chapter has evaluated whether natural resource use, as viewed through the WEF nexus lens, provides a useful basis for guiding integrated water, energy and land management, by studying the total environmental burden of human activity across food and non-food sectors in 189 countries. The insights from this assessment show how the partiality of WEF-centric analysis overlooks major pathways of water, energy and land use and risk across both individual countries and globally. The blindspot of WEF-centric assessment is most noticeable in relation to the energy system where food-related sectors appear to make a minor contribution to national energy footprints and high risk energy use [1]. However, even in the case of water and land, where food systems analysis capture the majority of national resource use and associated risk, non-food sectors still account for a large contribution of resource use (See Figure 5.2). Figure 5.6 illustrates how the contribution of non-food sectors to water and land use is only visible when studied from a consumption-based perspective and highlights the need for such a whole supply chain approach to identify the underlying consumption drivers of resource use across the WEL system.

By studying water, energy and land footprints from a cross-sectoral perspective, this chapter makes several contributions to the understanding of research and policy priorities in relation to nexus-based assessment. This assessment represents the first attempt to quantify the resource accounting boundary of WEF-centric analysis in relation to resource pressures and risks both for individual countries and the global economy. The insights from this highlight the need for nexus assessment to be extended beyond food sectors to the rest of the economy. Specific sectors of influence identified within this study, but which do not currently fall within the scope of the WEF-nexus research and policy agenda, include construction, textiles and apparel, transport, energy production and service sectors. To navigate the policy priorities borne from the multi-sectoral nature of water, energy and land use, a triage-based approach is suggested. The importance of food-related sectors within the 'triage' of national and global consumption pressures across the WEL system are important within the context of water and land management but insignificant in relation to energy management. Hence, the food system occupies an important role in relation to integrated water and land management, but not - as is currently believed - an important sector for addressing energy use.

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[1] Contrary to the global trend, national food demand appeared to be a more significant sources of high risk energy use in Kazakhstan and Russia. This is explained by the high levels of food import in these countries from energy insecure countries (FAO, 2019; World Energy Council, 2018).

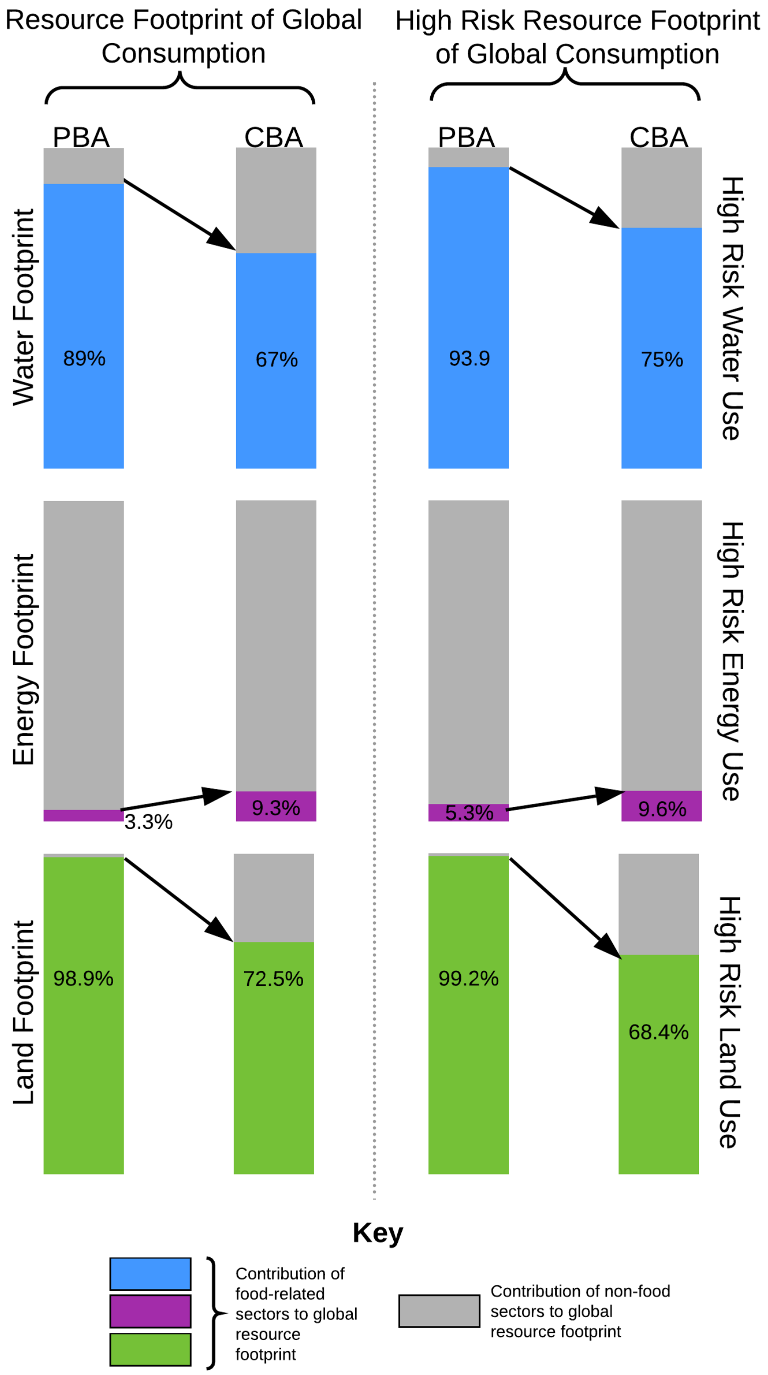

Fig. 5.6 PBA and CBA of food-sector pressures across the WEL system

Plots comparing the contribution of food-related sectors (coloured) and non-food sectors (grey) to the water, energy and land footprint of global consumption (left) and high risk resource footprint of global consumption (right) using a production based accounting (PBA) and consumption based accounting (CBA) approach to environmental footprinting.

Third, by evaluating the combined effects of sectoral and spatial boundary setting of country footprints across the WEL system, the appropriate scope for nexus-based assessment is revealed for both food sectors and non-food sectors. Within this context, national-scale footprinting of a country's resource use, which is the most common unit of nexus assessment (Albrecht et al., 2018), appears incapable of capturing the totality of consumption and production pressures across the WEL system. Accordingly, the nexus research agenda should refocus on national resource use embodied in global supply chains to inform key policy priorities.

The importance of multi-sectoral analysis is not only pertinent to the study of the water-energy-land nexus, as demonstrated in this study, but also several other applications. First, multi-sectoral analysis can help identify and evaluate possible rebound effects induced by sustainability measures where income savings or moral licensing shift consumption, and its associated environmental impacts, from target sectors to other production systems (Wood et al., 2017). Second, resource footprinting undertaken across all aspects of human activity can help to inform more coherent, comprehensive, and transformative pathways for living well within planetary boundaries (O'Neill et al., 2018). Third, an economy-wide approach to resource accounting can help to highlight the relative importance of technological, economic and demographic factors for the environmental burden of countries and in turn provide a more systematic evaluation of the changes required to bring about more sustainable economies.

As well as advancing understanding of sectoral priorities of countries in relation to the WEL system, this assessment highlights several data gaps which hinder more accurate and policy-relevant analysis at such scales. These concern sectoral resolution of economic accounts, environmental accounts and resource risk measures. The sectoral resolution of national economic and environmental accounts limits understanding of specific consumption activities responsible for resource use due to products, commodities or services being grouped into broad categories, such as 'Food and Beverages', 'Transport', or 'Textiles and Apparel'. The limited granularity of such data invariably undermines the reliability of sectoral consumption-based resource footprints since sectoral dependency coefficients,used to define the 'production recipe' of sectoral output, assume homogenous prices and resource intensities of products, commodities or services within a sector. This aggregation has been shown to under- or over-estimate resource fluxes along countries' supply chains (*cf* Lenzen, 2011; Steen-Olsen et al., 2012; Suh, 2004; Suh et al., 2004; Zhang et al., 2019). However, methodological advances and improvements in the availability of data to enable country resource footprinting at higher sectoral resolution offer a promising avenue for nexus assessment. Methodologically, approaches linking physical production data to MRIO accounts has allowed for more precise footprinting of sub-sectors in food (Croft et al., 2018), construction (Wan Omar et al., 2014), and other sectors (Moran et al., 2016). In terms of data availability, the number of countries with programmes on environmental-economic accounting has steadily increased in recent years and the UN's 2020 report on the Global Assessment of Environmental-Economic Accounting and Supporting Statistics promises near-term improvements in the scope and frequency of national economic and environmental reporting (UN, 2019). Several ongoing projects employing company-level data also stand to transform understanding of the drivers of water, energy and land use embodied in critical supply chains (*cf* PIK, 2019; RIHN, 2019; SEI-GCP, 2019). Although improvements of the Eora (2019) database were out of the scope of this assessment, this study highlights critical sectors and countries of interest where more detailed assessment is needed and where improvements in modelling capacity should be targeted (See Tables 5.1 and 5.2). Moreover, the sectoral and spatial resolution of the Eora (2019) database is set to improve in coming years due to ongoing efforts to incorporate company, city, and household consumption and production data (RIHN, 2019).

The limited sectoral and spatial detail of the available indices of resource risk have resulted in the necessary application of a single risk measure to be associated with each of water, energy and land use in a given country. This invariably ignores the heterogeneity of resource insecurity within countries. Within the context of the risk-related environmental footprint, advances in sectoral and spatial detail are still in their infancy. However, recent attempts to link high resolution geo-referenced environmental datasets to MRIOA consumption sectors via concatenating sector-specific pollution and risk maps to MRIO production sectors offers a disciplined methodological approach to distinguish the severity and location of resource risks different imposed by different sectors. Such methodology has enabled spatially explicit mapping of country greenhouse gas emissions (Kanemoto et al., 2016), biodiversity (Moran & Kanemoto, 2017), and air pollution (Moran & Kanemoto, 2016) and is likely to be extended to water, energy and land in coming years as part of a project at the Research Institute for Humanity and Nature in Japan (RIHN, 2019).

The current WEF nexus agenda continues to shape research and policy priorities around the integrated management of water, energy and land resources, in both individual countries and globally. Although policy decisions made in relation to food consumption and production are of major consequence to natural resource management, the food sector is not the only area where consumption and production decisions will strengthen or weaken progress against water, energy and land sustainability goals.

Chapter 6

A supply chain analysis of the global water-energy-land system

> Apple can say it is completely ‘green’ because it is a brand with no factory, but if it doesn’t manage its supply chain, these are just empty words
>
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>
> *Jun, 2011*

6.1 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.

Profiles of sectoral pressures across the water-energy-land (WEL) system are poorly understood owing to the use of aggregate resource footprinting across these domains. Although instructive, the resource footprint of sectors does not reveal how its resource demand is imposed across supply networks. This matters since the distribution of resource use across supply networks might vary between sectors, demanding entirely different management approaches to ensure their sustainability. Figure 6.1 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.

By decomposing water, energy and land use across country and sector supply chains, this chapter accordingly 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 nexus-based assessment to Scope 1 and Scope 2.

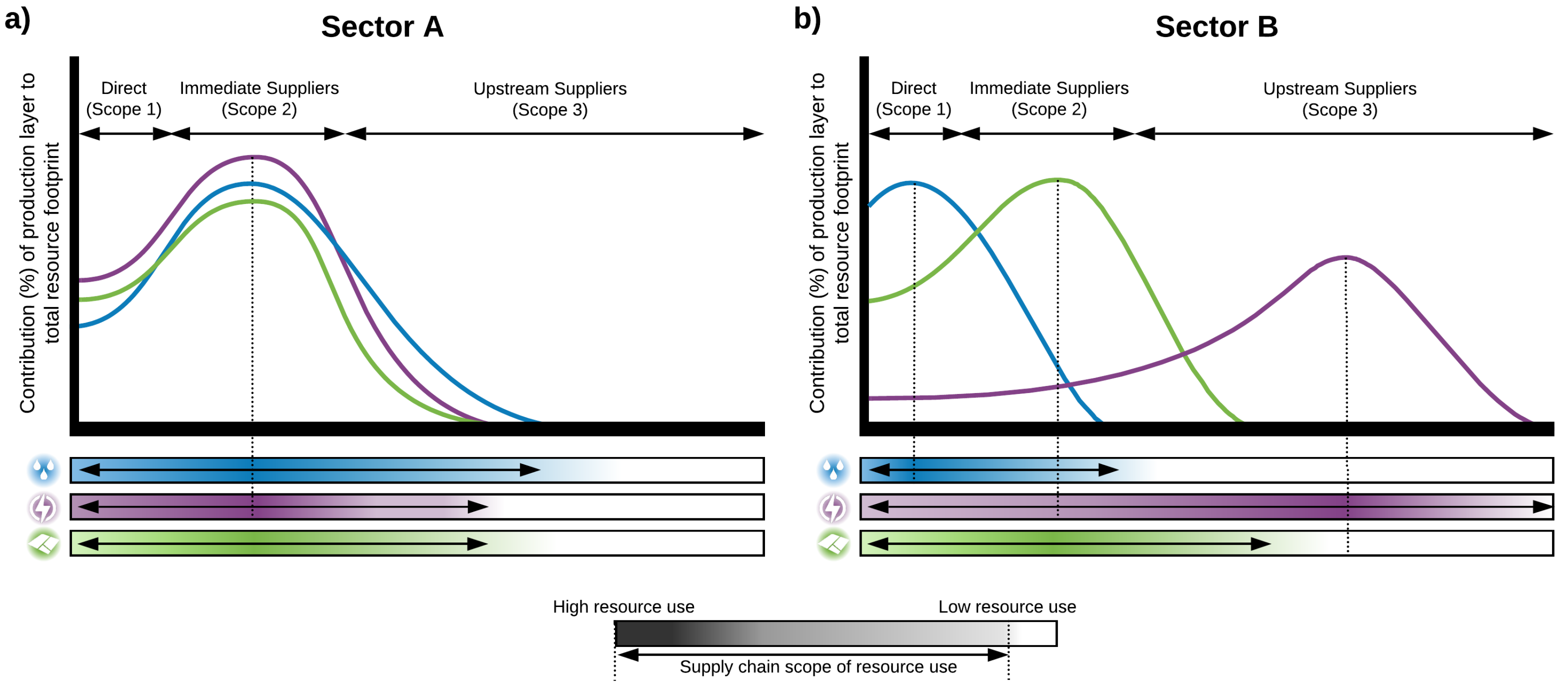


Fig. 6.1 Profiles of resource use across supply networks
Schematic exemplifying different profiles of water, energy and land footprints in sector supply networks. Sector A illustrates a sector where water, energy and land use is concentrated at the same stage (Scope 2) of its supply network, implying 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.

This chapter begins by reviewing existing scholarship on the decomposition of water, energy and land footprints across country and sector supply networks. Section 6.2 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 6.4, 6.5 and 6.6, convey the importance of different supply chain scopes for integrated management of pressures across the WEL system. The application of this analysis is demonstrated by the further development of the UK case study, featured in Sections 4.3.3 and 5.5, to identify how the footprint of UK consumption on water, energy and land resources can be addressed through management of its supply network. Section 6.7 comments on the significance and limitations of these findings and their implications for future research on and management of the global WEL system.

Globalisation, outsourcing and subcontracting of production processes have led to an expansion in the supply networks of countries and sectors (Maluck & Donner, 2015). The increasing spatial and organisational complexity of supply networks has led to dependence on a greater number of remote suppliers (i.e. suppliers of suppliers) within global production and consumption systems (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).

The previous chapters of this thesis examine the spatial and sectoral distribution of national water, energy and land footprints and their potential insecurity by enumerating resource dependencies across their entire, global supply networks. The aggregate nature of environmental footprinting, whether weighted by risk or other dimensions, does not convey where in country or sector networks resource pressures are concentrated. The structure of input-output analysis lends itself to the assessment of sectoral impacts across different levels of their supply network. As shown in Section 6.2, the Leontief demand-pull model, introduced in Section 2.2.5, can be expanded to series of equations which evaluates supply chains at discrete production levels. This decomposition, termed 'Production Layer Decomposition' (PLD) allows for an assessment of resource use associated with different levels of production for different final consumers (e.g. regions, countries or sectors). Such disaggregation of resource across supply networks is possible due to the availability of cross-sectoral transactions data within MRIO databases. In the absence of equally detailed physical multi-regional input-output data, production layer decomposition cannot be achieved using process-based methodologies, such as Material Flow Analysis or Life-Cycle Analysis.

To date, the application of PLD has mostly been levelled at assessment of carbon emissions through sectoral supply chains (*cf* Hertwich & Wood, 2018; Kucukvar & Samadi, 2015; Lenzen et al., 2018; Rodríguez-Alloza et al., 2015; Schmidt et al., 2019). 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. (2012b) 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; Lenzen, 2008b; Malik et al., 2016) or regions (Veiga et al., 2018). For land, no cross-country applications of PLD were found at the time of writing, possibly because of the focus of nexus-based assessment on the WEF nexus for which pressures on land are only indirectly captured. Accordingly, there is a clear need to understand how water, energy and land use *and* risk is distributed across national and sectoral supply networks.

6.2 Methods

This section outlines how PLD is applied to the assessment of country and sector resource pressures across the WEL system. Section 6.2.1 outlines the modelling principles behind PLD and Section 6.2.2 describes the additional data requirements and modelling demands of such technique. Since PLD relies on the conventional Leontief demand-pull model, and principles associated with Input-Output analysis, the strengths and limitations of MRIOA are not described here, but can be found in Sections 2.2.5 and 4.4.

6.2.1 Modelling principles

PLD enables the unravelling of the supply chain of a given sector or set of consumption activities (e.g. linked to global, national or sectoral demand) to assess their production requirements and associated environmental impacts at different stages of their 'production tree' (Kitzes, 2013).

Quantitatively, PLD of a country or sector's resource footprint, F is achieved by expressing the Leontief demand-pull equation $F = f\mathbf{L}y$, derived in Section 2.3, as a set of power terms corresponding to subsequent production levels i and their associated resource use F_i:

$$F = F_1 + F_2 + F_3 + ... = fy\mathbf{I} + fy\mathbf{A} + fy\mathbf{AA} + ... = fy[\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + ...] \qquad (6.1)$$

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 $\mathbf{A}$ matrix are below 1, the power series 6.1 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 are examined which capture on average >95% of overall water, energy and land use within countries and sectors. PLD is also applied to evaluate the contribution of country and sector production levels (and scopes) to high risk water, energy and land use, using the risk-related indices introduced in Section 4.2.4.

6.2.2 Data

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-level resource footprints, the full Eora (2019) database is used. The caveats associated with using a lower resolution version of the Eora (2019) database are discussed in Section 6.7. The analysis within this chapter relies on the same underlying environmental data and resource risk assessment as Chapters 4 and 5.

6.3 Analysis

The PLDs of water, energy and land footprints are analysed from national and sectoral perspectives in Sections 6.4 and 6.5. Section 6.4 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 6.5 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. Lastly, Section 6.6 illustrates how the application of PLD to UK consumption can help to inform research and policy priorities for integrated management of its water, energy and land footprint.

6.4 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 countries' 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 different production levels to national resource footprints.

Figure 6.2 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 fooootprints (n = 143), as indicated by the pink shading of countries in Figure 6.2. 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 were identified in Chapter 4. Moreover, as shown in Figure 6.3, 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-level 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 6.2 and 6.3. 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 the 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 6.4 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. 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 6.4).

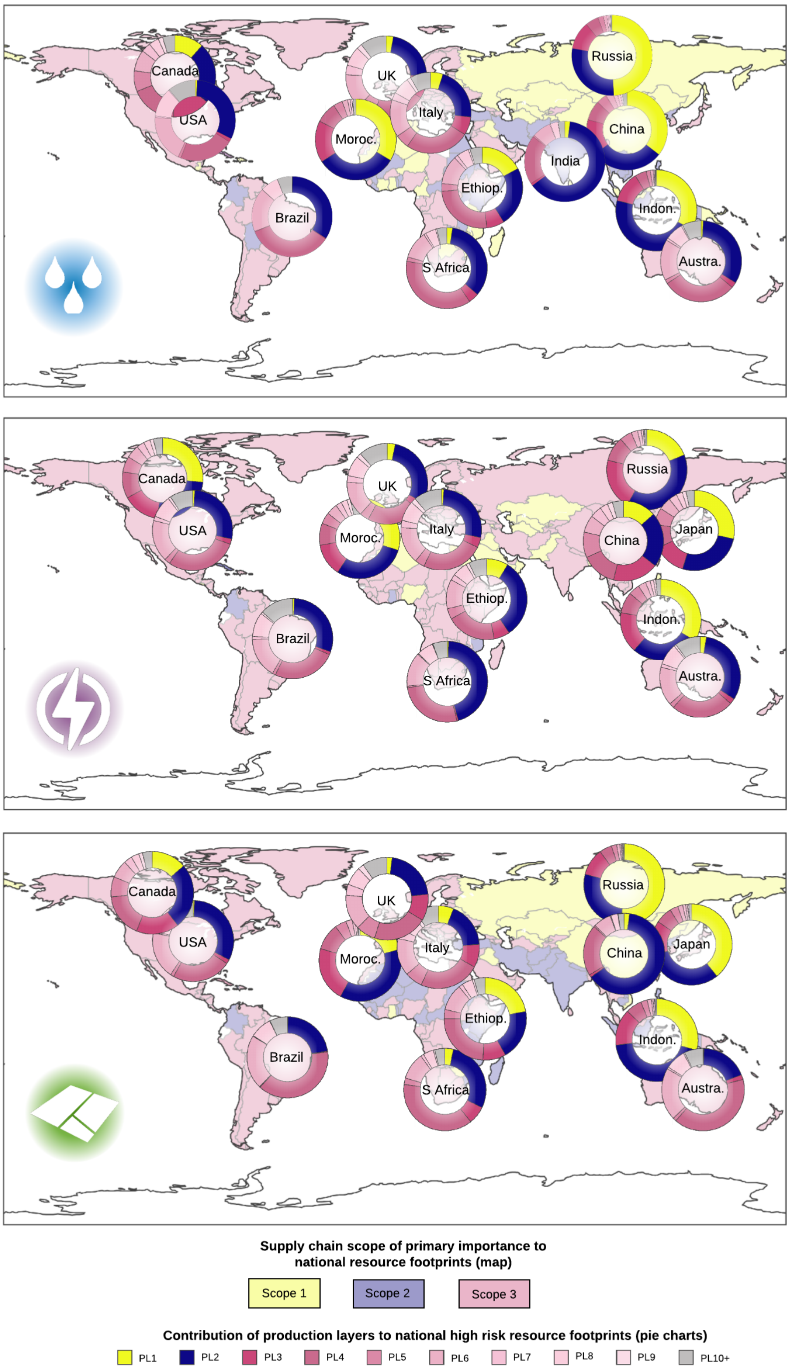


Fig. 6.2 Contribution of Scope 1-3 suppliers to national WEL footprints
Choropleth map illustrating the supply chain scope (1-3) of primary importance to national water, energy and land footprints. Country colouration is based on which supply chain scope (1-3) accounts for the largest share (i.e. more 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 (identified in Chapter 4.

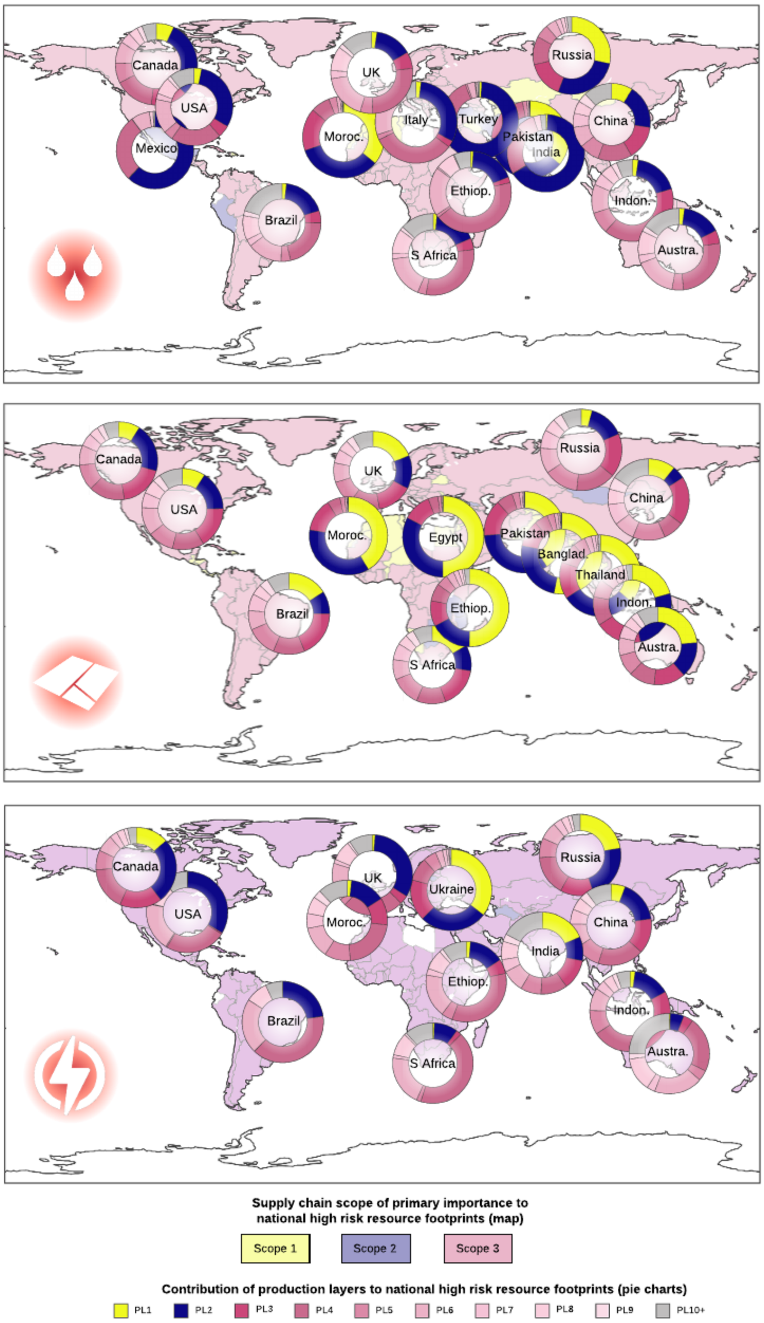


Fig. 6.3 Contribution of Scope 1-3 suppliers to national WEL risks

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 (identified in Chapter 4.

Table 6.1 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 Tm^3 (13.9%)	54.9 EJ (11.7%)	0.493 Gha (15.9%)
Scope 2	3.36 Tm^3 (35.4%)	131 EJ (27.8%)	1.07 Gha (34.6%)
Scope 3	4.80 Tm^3 (60.6%)	285 EJ (60.6%)	1.53 Gha (49.5%)

Table 6.2 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 Tm^3 (8.6%)	5.89 EJ (32.3%)	35Mha (3.3%)
Scope 2	1.01 Tm^3 (50.5%)	5.06 EJ (27.8%)	302Mha (28.1%)
Scope 3	8.18 Tm^3 (41%)	7.26 EJ (40%)	740Mha (68.7%)

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 6.1 and 6.2. 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.

6.5 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 nexus 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 6.5 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 (2019) database. The *Agriculture* sector is a suitable entry point for discussing this analysis given the importance assigned to agricultural production in nexus 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 6.5-1). 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 6.5-1 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 6.5-4). 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 6.5-5), *Wood and Paper*(Figure 6.5-6), and *Construction* (Figure 6.5-14). 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 6.5). For example, direct resource use accounts for the large contribution to energy footprints in *Electricity, Gas and Water* (Figure 6.5-13), *Transport* (Figure 6.5-19), *Mining and Quarrying* (Figure 6.5-3), and *Petroleum and Mineral products* (Figure 6.5-7) sectors but an insignificant proportion of water and land footprints.

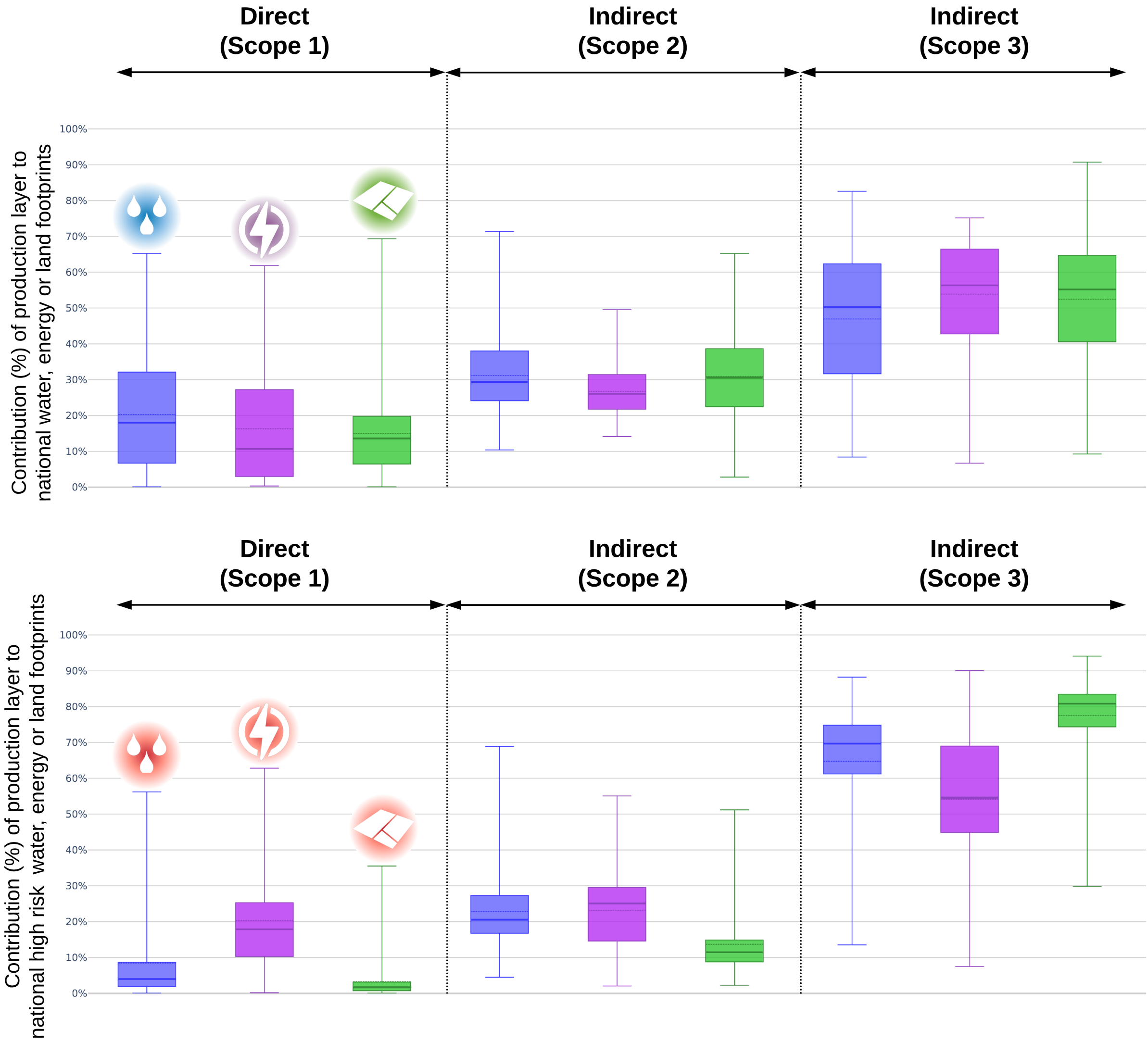


Fig. 6.4 Distribution of Scope 1-3 production embodied in national WEL pressures

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 represents inter-quartile range; mean values = dashed lines; median values = solid lines.

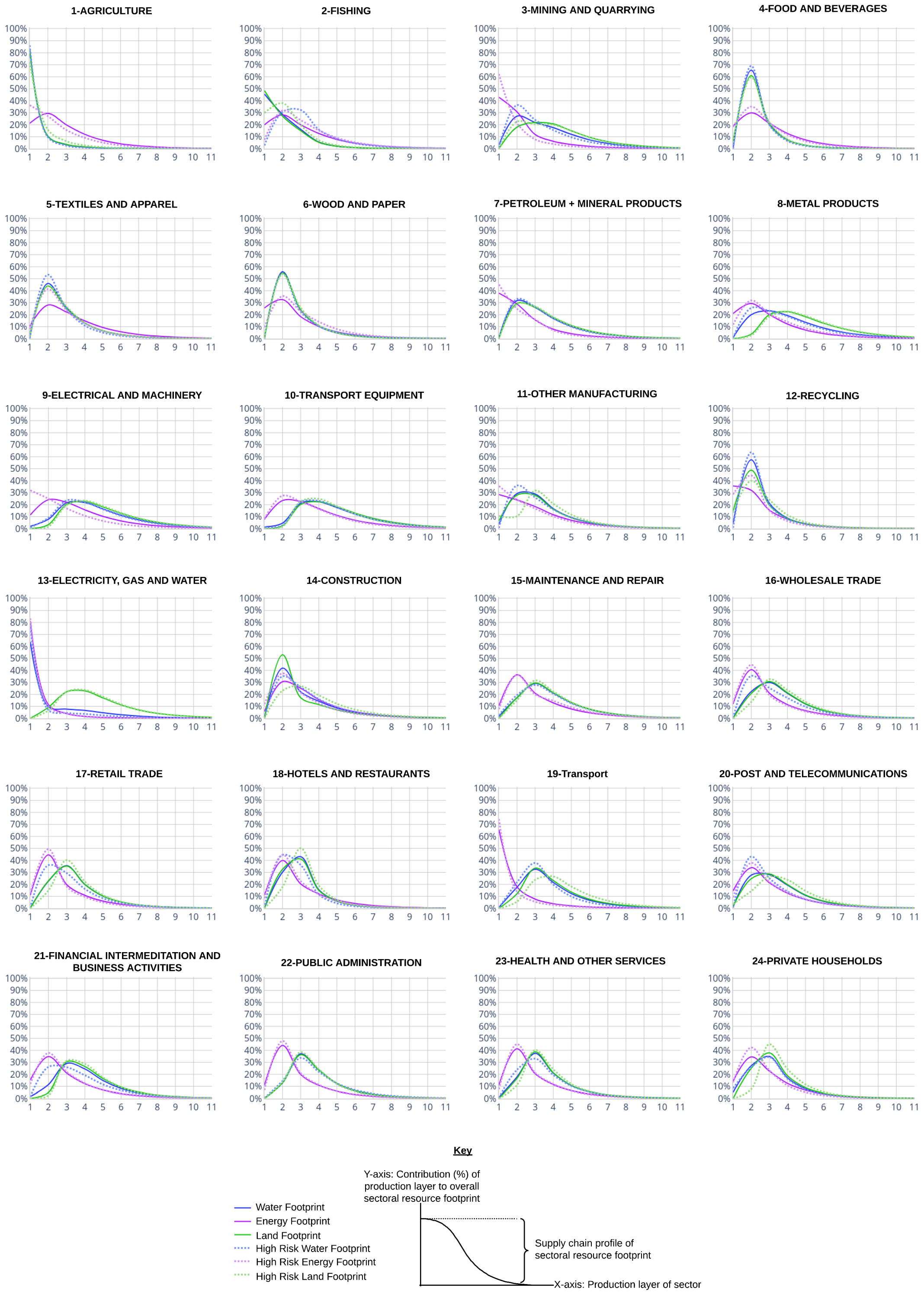


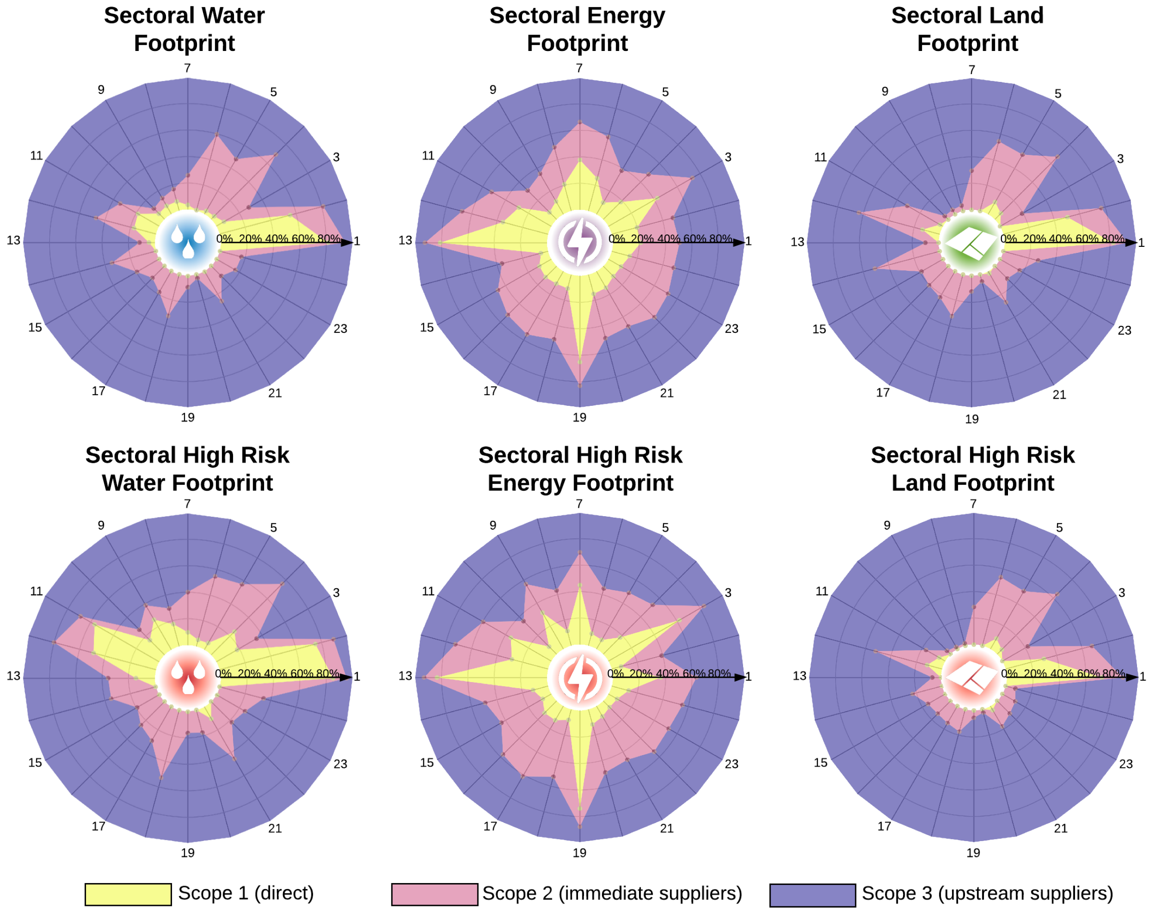
Fig. 6.5 Supply network decomposition of WEL pressures in major global sectors
Series of plots illustrating the contribution of different production layers (z-axis) to the water, energy and land footprints (y-axis) of 24 global sectors.

In contrast, resource use in some sectors are highly diffuse across their production networks - see *Metal Products* (Figure 6.5-8), *Electrical and Machinery* (Figure 6.5-9), *Transport Equipment* (Figure 6.5-10), and *Other Manufacturing* sectors (Figure 6.5-11). 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.

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 6.6 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 6.5.



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. 6.6 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 nexus-based 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.

6.6 Hotspots for water, energy and land management in UK supply chains

Further to the study of the spatial and sectoral distribution of the UK's water, energy and land footprint, featured in Chapters 4 (section 4.3.3) and 5 (Section 5.5), this section summarises where such consumption pressures arise in the UK's supply network. Interestingly, the resource demand of UK consumption across all components of the WEL system is more highly concentrated in the upstream scope of its supply network when compared with the global average. In the UK, direct production is responsible for just 2.9% of its water footprint, 3.2% of its energy footprint and 2% of its land footprint compared to the global average of 20.2%, 16.3% and 15% respectively. Figure 6.7 shows that Scope 2 production is responsible for a larger proportion of the UK's pressure on global water, energy and land resources (WF = 21.5%, WR = 29.3%, EF = 21.3%, ER = 14.7%, LF = 13.7%, LR = 32.5%). However, Scope 3 suppliers account for the majority (>60%) of the UK's pressure across global water, energy and land resources. When compared with the global average, a greater proportion of the UK's resource footprint and high risk is indirect (i.e. in Scope 2 and 3 of its supply chain). This is true even when comparing the UK to the OECD average, except in relation to the UK's resource footprint, which is more heavily concentrated (18.8%) in scope 1 of its supply chain compared with the OECD average (10.33%).

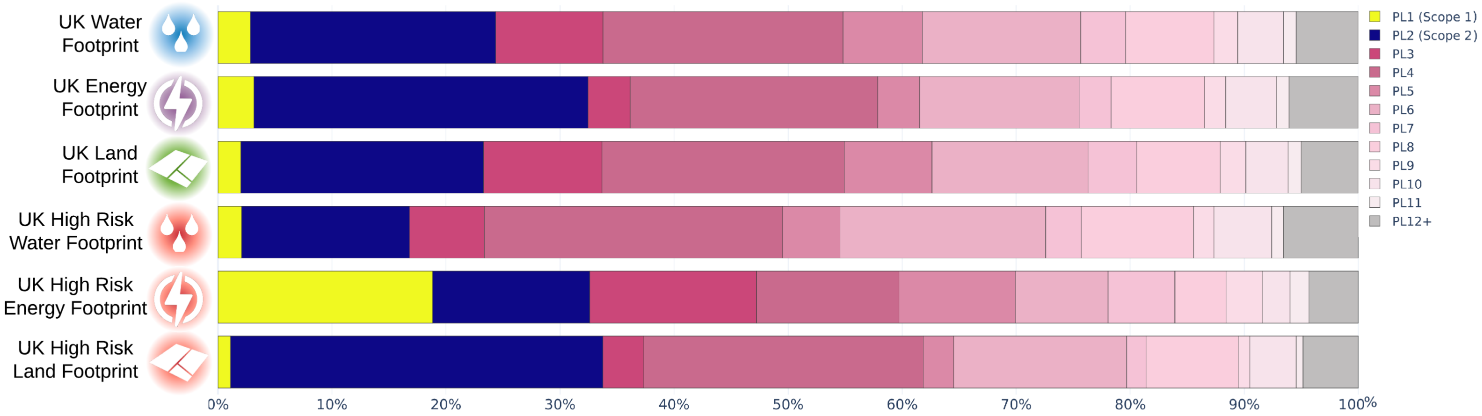


Fig. 6.7 Production Layer Decomposition of the UK’s resource footprint

Bar chart illustrating the contribution of production layers (PLn) in the UK’s supply network to its global water, energy and land footprint.

Within the context of the UK's resource high risk water footprint, third level suppliers account for over three quarters (76.7%) of impacts. When comparing each individual production layer of the UK's supply network, Scope 2 suppliers are found to account for the greatest contribution to the its overall water footprint (21.5%), energy footprint (29.3%) and land footprint (21.3%). In contrast, the importance of supply levels to the UK's high risk resource footprint varies between components of the WEL system. Third level suppliers contribute most (26.2%) towards the UK's high risk water footprint; direct production is most significant (18.8%) in relation to the UK's high risk energy footprint; and, Scope 2 suppliers represent the greatest source (32.6%) of UK exposure to high risk land use. Overall, this analysis shows that truncating analysis of the UK's consumption to only Scope 1 and 2 suppliers would overlook between 60-80% of its footprint across global water, energy and land resources.

6.7 Discussion

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. The aggregate nature of conventional environmental footprinting disguises the profile of resource use across supply chains and the associated entry points for their effective management. By decomposing the water, energy and land footprints of countries and sectors across supply chain layers, this chapter 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 chapter 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, nexus 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 6.5, 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 assessment 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 chapter, 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, nexus 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. (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 thesis research.

In addition to the methodological and data limitations noted in Section 4.4 and Section 5.6 which surround environmentally extended MRIOA and the risk-based resource footprinting approach employed in this thesis, additional caveats surround this chapter'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 conflates a large proportion of economic and environmental activity. Where appropriate, the significance of specific production layers in Scope 3 is made explicit (see 6.5, Section 6.4 and Section 6.7.

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., 2013b), 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 chapter. 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 x 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.

In recent years, the research and policy community has called for a need to examine the entire supply network of consumption to understand more fully the environmental burden of humanity. In response, many techniques have been developed to evaluate the total environmental footprint of countries and sectors within such a context (See Chapter 2). However, the aggregate nature of resource footprinting does not distinguish the origins of resource use in country or sector supply networks. For example, analysis of country and sector resource footprints in Chapters 4 and 5) reveals important sources of resource demand across the WEL system, but does not identify where interventions should be targeted within these critical contexts. By studying how country and sector pressures on the WEL system are distributed across their entire supply network, this chapter reveals their underlying supplier source. Such a perspective highlights the need to refocus the nexus agenda around upstream suppliers, indirect resource consumption and the distinct profiles of water, energy and land use across sector supply networks. Although measures are being taken to improve reporting and regulation of Scope 3 impacts of sectors on greenhouse gas emissions (*cf* Farsan et al., 2018; Redevco, 2019; Richards, 2018), this assessment highlights the need to extend this agenda to water, energy and land resources.

Chapter 7

Discussion

> Ask anyone what's wrong with consumer society and they'll almost certainly tell you that it has made people "too materialistic". We are obsessed, we're always told, with things, and our material engrossment is killing the environment, our relationships and our spiritual lives. It strikes me that precisely the opposite is true: we are not materialistic enough. Consumerism demands the fast and careless use of materials. It relies on our detachment from and incomprehension of the material world. Do you know where the components of your TV or your computer come from? Do you even know what they're made of? Have you ever considered how these materials were extracted, which peoples needed be displaced so that their lands could be mined or logged?
>
> *George Monbiot (1999)*

7.1 Introduction

Measures which address the degradation and over-exploitation of natural resources are urgently needed, in individual countries and globally (UNDP, 2014). However, the extraction and use of natural resources is highly interconnected, spatially and sectorally, within a complex web of global interactions and feedbacks. The provision of goods and services relies on dense networks of producers whose activities are linked across multiple countries and sectors. As such, the link between consumption decisions and their impact on natural resources can be difficult to disentangle. The resource footprint has emerged as a useful approach to assess the global demand countries impose on natural resources through complex pathways of production, consumption and trade. Although instructive, the resource footprint of a country does not meaningfully distinguish where its resource use is imposed in relation to geography, sector, and supply chain scope. Consequently, there remains a mismatch between the global scale of conventional footprinting analysis and the sub-global scale of decision making where choices ultimately shape the sustainability of countries and sectors.

By contextualising resource footprinting analysis by spatial, sectoral and supplier source, this thesis brings into sharper focus the pathways of demand for three critical resources: water, energy and land. Decisions made in relation to water, energy and land use will strengthen or weaken progress on other development objectives such as food security (Endo et al., 2015), technological growth (Ringler et al., 2013), and public health (WWAP, 2015). Despite their importance, global priorities for managing water, energy and land resources are poorly understood owing to their conventional separate assessment and the limited spatial and sectoral scope of integrated resource analysis (Taherzadeh et al., 2018). This thesis develops a flexible framework for examining global and national priorities for managing pressures across the water-energy-land (WEL) system by combining macroeconomic data, environmental accounts, and resource risk indices. The data and findings arising from this analysis, reported in Chapters 4, 5 and 6, explore these priorities for 189 countries, 19 global regions, and different sectors of the economy. Consumption-orientated analysis within this context enables national, regional and sectoral pressures across the WEL system to be traced to their source and not only national borders, via an analysis of resource interdependencies embodied in international trade.

Since the empirical chapters of this thesis contain separate discussions pertaining to their analysis, this final discussion section will take a broader perspective. Although, an abridged summary of each chapter is provided for completeness here. Section 7.2 comments on the contribution of this thesis to the fields of nexus analysis and resource footprinting and their implications for integrated environmental assessment. Section 7.3 highlights the main uncertainties associated with analysis and how these can be overcome. Section 7.4 highlights promising avenues for future research emerging from this analysis. Lastly, 7.5 identifies the priorities and mechanisms required to translate the findings in this thesis into practical recommendations for policy.

7.2 Building a flexible framework for nexus assessment

This thesis represents a major point of departure from existing scholarship on the WEL system, in methodology, analysis, and application. Methodologically, nexus assessment lacks a unifying approach to assess, compare and contextualise the pressures of countries and sectors across the WEL system (Taherzadeh et al., 2018). This is symptomatic of the dominance of case study analysis in nexus scholarship which has promoted the use of models, approaches and data with limited wider application (*cf* Dale et al., 2015; Kirschke et al., 2018; Talozi et al., 2015). This thesis develops an alternative research paradigm for nexus assessment. By prioritising flexibility, careful attention was paid to construct a methodological framework capable of examining pressures across the WEL system from the perspective of multiple countries and sectors, and in relation to changing policy priorities and questions. Such an approach has several advantages over prevailing biophysical models and socio-technical analysis which have dominated nexus assessment (discussed in Chapter 2). The underlying use of the Eora (2019) MRIO database enables self-consistent water, energy and land footprinting of countries and sectors without truncation by spatial, sectoral or supply chain scope. Although computationally intensive, such a data-driven approach also significantly reduces the time cost, and potential errors (e.g. double counting or mis-allocation of resource use), of using physical commodity and environmental accounts to trace pathways of resource use in complex and globalised supply chains (Hubacek & Feng, 2016). As a top-down approach, MRIOA can also easily accommodate new economic and environmental datasets which stand to improve the scope and precision of analysis within this thesis. The Eora (2019) database in particular contains a large amount of environmental data, in addition to water, energy and land accounts, which is set to increase in spatial and sectoral resolution over the coming years, and which can be easily incorporated to the methodological framework developed in this thesis. This is demonstrated in relation to non-WEL resource footprints on Page 161 and in Figure 7.2.

Analytically, this thesis establishes a foundational understanding of national water, energy and land resource dependencies within the world economy. National interdependencies across the WEL system are shown to be (i) driven by remote international trade (see Chapters 3 and 4), (ii) multi-sectoral in source (see Chapter 5), and (iii) extend far down production networks (see Chapter 6). Each chapter makes a unique contribution to the understanding of pathways of resource use across the WEL system. Chapter 3, published in the *Journal of Cleaner Production* (Taherzadeh & Caro, 2019), illustrates the highly globalised and sectorally diverse nature of water and land use embodied in international soybean trade. This assessment found that soybean trade is responsible for around one-third of soybean related green water use and soybean related land use and is primarily driven by demand for animal feed. The learning outcomes of this chapter informed the criteria for analysis in subsequent chapters, namely the need for more detailed macro-economic data to capture resource use across global supply chains and multiple sectors. The contribution of domestic production and international trade to natural resource use is examined more systematically, using MRIOA, in Chapter 4. By decomposing resource footprints by source, Chapter 4 reveals that countries and sectors are more exposed to water, energy and land risks via international trade than is the case for domestic production.

This assessment represents the first global study to distinguish the severity and source of national and sectoral pressures across the WEL system. Building on this, Chapter 5 examines the contribution of sectors to water, energy and land resource use within this context. To date, nexus assessment has focused chiefly on food-related sectors. However, Chapter 5 examines both food and non-food sectors as a source of resource demand and risk across the WEL system. This assessment reveals the importance of extending nexus assessment to non-food sectors to capture fully the drivers of resource use across the WEL system. Lastly, Chapter 6 decomposes country and sectoral resource footprints across their supply networks to identify the main suppliers (direct, immediate or upstream) contributing towards their water, energy and land use. This assessment revealed the unique supply chain profiles of water, energy and land use within and between countries and sectors. Scope 3 suppliers, which exist further upstream in supply networks, are found to be a significant source of pressure across the WEL system, highlighting the need for full supply chain reporting, engagement and management to improve the sustainability of country and sector consumption.

The flexibility of MRIOA used within the thesis can accommodate additional policy questions not explored here, by incorporating new environmental data, indicators, or scales of analysis, and by applying novel analytical techniques. This is crucial given the constantly changing landscape of industry, government and global policy and the moving targets which surround sustainability. An analysis of the spatial, sectoral and supply chain scope of other (i.e. non-WEL) national environmental footprints, shown in Figure 7.1 demonstrates this flexibility. Carbon emission CO2, particulate matter (PM10) and metal ore footprints were selected as additional sustainability indicators since they affect and are affected by decisions made in relation to water, energy and land resource. This abridged analysis, based on methods procedures featured in Sections 4.2.3, 5.3 and 6.2, reinforces the need for global-scale, multi-sectoral and fully supply chain accounting of environmental impacts driven by national consumption. On average, non-domestic production is found to account for nearly one-third of national CO2 footprints, over 20% of national PM10 footprints and over one-third of national metal ore footprints (Figure 7.1). Sectorally, food-related sectors are responsible for a minor contribution to national CO2 footprints (mean = 11.6%; median = 6.4%), national PM10 footprints (mean = 20.9%; median = 21.6%), and national metal ore footprints (mean = 6.7%; median = 5.7%). In terms of supply chain impacts, direct (Scope 1) production is also responsible for only a small proportion of national CO2 footprints (mean = 7.6%; median = 1.6%), PM10 footprints (mean = 12.3%; median = 3.3%) and national metal ore footprints (mean = 2%; median = 0.5%). Consequently, as with nexus assessment of the WEL system, truncating analysis of national consumption on CO2 emissions (and the climate system), air pollution and metal ore depletion by spatial, sectoral and supply chain scope has the potential to overlook countries' impacts across these systems.

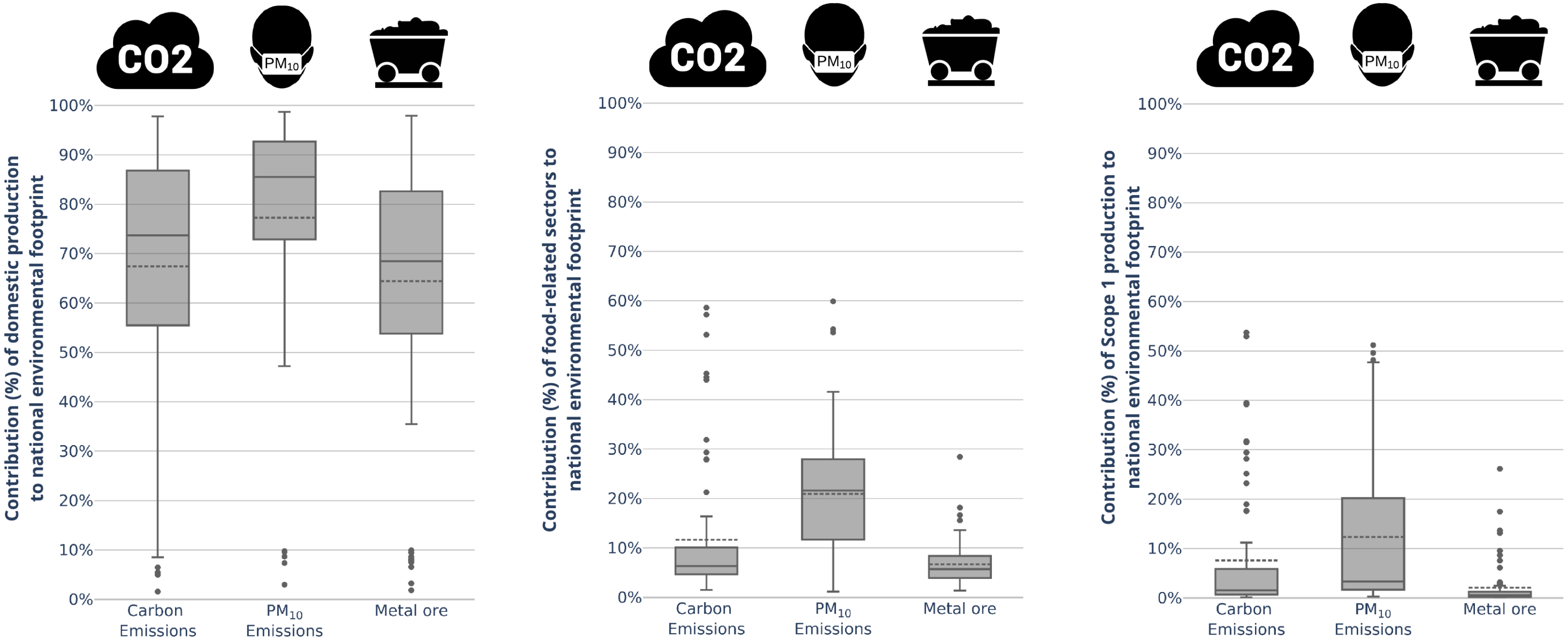


Fig. 7.1 Spatial, sectoral and supply chain scope of non-WEL footprints

Box plot showing the application of methods developed within this thesis to assess the spatial, sectoral and supply chain scope of national carbon emission CO2 footprints, particulate matter (PM10) footprints and metal ore footprints. Filled circles represent potentially outliers, calculated as being greater than three times the inter-quartile range above quartile three or below quartile one.

To further the application of this thesis to scholarship all data and analysis arising from Chapters 3, 4, 5 and 6 have been made available at Taherzadeh (2020), including the main programming code required for the reproduction of analysis in Chapters 4, 5 and 6, which is also featured in Appendix A of this thesis. The decision to use open-access data in all assessments also enables reproducibility and extension of the analysis within this thesis by other users. However, the findings of this analysis and its underlying data must be utilised with an understanding of their associated limitations, which are discussed in Section 7.3 along with the factors influencing the reliability and uncertainty of analysis across this thesis (Section 7.3.1).

7.3 Limitations

Typically the certitude attached to policy analysis of complex systems fails to reflect fully the range of uncertainties and assumptions underlying the modelling process (Stirling, 2010). Within the context of this thesis, deep uncertainties characterise the pathways of resource use across the WEL system (WEF, 2014). Several uncertainties characterise the proposed methodological framework outlined. Quantitative examination of these uncertainties is beyond the scope of this thesis for several reasons. First, the scope of this analysis renders the uncertainty analysis prohibitively costly in terms of computing time. In practical terms, uncertainty analysis would involve a perturbation of different components of the model, in isolation and combination, within a defined range, to assess the sensitivity of final resource footprint values to changes in inputs. Such an exercise could be achieved via Monte Carlo analysis, as in Lenzen et al. (2010), but would demand iterative re-computation of the resource requirements matrix - a computationally costly process - which would take approximately 1.89m hours of computation time [1], across 189 countries. Second, not all of the uncertainty ranges associated with the model inputs are readily known and some are simply estimated. As such, a sensitivity analysis of the model might not produce meaningful insights. Lastly, the explanatory power of comparing the resource footprint estimates calculated within this thesis with other MRIO databases is limited due to poor sectoral, spatial and temporal concordance between the Eora (2019) MRIO database and other MRIO databases (e.g.

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[1] Calculated based on Lenzen et al. (2010) use of 5000 model runs to estimate uncertainties for a given country's resource footprint, at 2 hours per job as defined in Figure 2.6

GTAP, EXIOBASE, and WIOD). Consequently, a qualitative discussion of the uncertainties involved in this analysis is provided within this section.

Since the limitations of all four empirical chapters of this thesis are discussed in their respective chapters (see Sections 3.4, 4.4, 5.6, 6.7), these are only recapitulated here as part of a broader reflection on the limitations innate to economy-wide modelling of country and sector resource footprints.

7.3.1 Factors influencing model reliability

Spiegelhalter & Riesch (2011) identify five factors influencing the reliability of model-based risk analysis which provide a framework for this discussion:

1) **Data**: the availability and uncertainty of information related to the system being studied

2) **Parameters**: chosen model variables constructed from available data

3) **Model structure**: decisions concerning the functional characterisation of relationships within the system being studied based on model variables, methodological assumptions, and limited understanding of actual cause-effect relationships

4) **Indeterminancy**: known inadequacies relating to the explanatory power of model observations in relation to the dynamic relationships of the system it studies

5) **Ignorance**: unknown inadequacies relating to the analysis, framing and interpretation of model observations

The influence of data, parameters and model structure constitute base-level uncertainties, whilst 4 and 5 relate to the entire modelling process. As such, these factors are discussed within the context of this thesis research in two parts.

7.3.2 Data, parameters and model structure

The analysis in this thesis relies on different data from multiple sources. These can be categorised into (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 thesis 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.

Data processing is necessary in or order for these raw data to be practically employed are parameters in the assessment of country and sectors pressures across the global WEL system. For national economic and environmental accounts, Lenzen et al. (2012a) perform several balancing procedures in the construction of the Eora (2019) database, used in this thesis research, to reconcile disparate, unaligned, conflicting and unreliable information from multiple databases (e.g. UN Comtrade international trade database, National Input Output tables and main aggregate data, and input-output compendia from Eurostat and the OECD). These balancing procedures, reported in Lenzen et al. (2013b), including optimisation, quadratic programming and reliability-weighted constraints, mean values in the Eora (2019) database, used to calculate country and sector resource footprints, deviate from these raw data. The adherence of economic variables in Eora (2019) with the raw data in national economic accounts is summarised at www.worldmrio.com/quality/ where the database is also hosted. Lenzen et al. (2012a) notes, the adherence of larger values in Eora (2019) to raw data points, alongside an abundance of small and unreliable MRIOA elements do not compromise input-output multipliers and resultant footprint calculations. However, further uncertainty is introduced in the standardisation of these values in a single currency ($) based on the purchasing power between countries (Lenzen et al., 2013b). Although environmental accounts in Eora are preserved in their original form, the underlying data used to construct them includes assumptions about the relationships which govern demand for and supply of water resources (e.g. evapotranspiration, water retention, and crop growth), energy resources (e.g. energy conversion efficiency, substitutability and intermittency) and land resources (e.g. net primary productivity, land use classifications, and soil fertility). These assumptions also hold for the resource risk accounts used which rank countries' performance in relation to these factors.

The calculation of country and sector resource footprints using MRIOA is affected by the aforementioned data and parameter uncertainties in the Eora (2019) MRIO database as well as the fundamental assumptions of IOA, discussed in Chapter 2. Conventional MRIOA, outlined in Section 2.2.5, relies on the assumption that production-consumer relationships within the world economy are governed by a perfect equilibrium of market forces (i.e. supply and demand) and therefore can be treated as stable. Whilst this simplification is intended to render the calculation of country and sector resource footprint more straightforward, as shown in Chapter 2, it overlooks the dynamic state of economic networks and the changing roles of actors within them. Such a static analysis does not convey how pathways of resource use vary according to sub-annual changes in market conditions, procurement and patterns of consumption and production, and how these vary spatially. As such, MRIOA cannot readily explain how countries and sectors might adapt to risks associated with resource use in their supply chains. For environmental accounts used in this thesis research, summarised in Chapter 4, modelling assumptions also affect the reliability of country and sector resource footprint estimates. For example, water and land use values assigned to crop production are based on global or regional averages. While these values are invariably based on primary data collection, the extent to which they can be generalised reliably across spatial, temporal and sectoral scales is unclear. Resource risk indices for water, energy and land use in countries face similar issues of generalisation due to their aggregate nature. Here, the extent to which the availability and use of natural resources reflects their direct or indirect risk to end users is also based on a narrow, principally physical notion of resource scarcity or insecurity. The decision to (re)allocate risk categories to countries from the original resource risk datasets potentially abstracts this relationship further, as noted in Chapter 4.

Evaluating the reliability of observations in this thesis is challenging due to the multiple sources of uncertainty noted above. Varying model input data, parameters and structure has the potential to reveal where estimates of country and sector footprints are most sensitive to change and how robust they are to extreme values. However, in the absence of known probability distributions of the underlying data (e.g. based on physical flows of resources, real groundwater reserves or crop, or actual agricultural land use), sensitivity analysis cannot explicitly quantify uncertainties associated with resource footprint analysis. Improvements in data availability and direct observations of coupled socio-ecological interactions will help to address this. However, other broader concerns about our ability and knowledge to study such complex systems, from indeterminacy and ignorance of the modelling process, will not be allayed by a reduction in statistical uncertainty.

7.3.3 Indeterminancy and ignorance

A major assumption of the calculation of country and sector footprints in this thesis is that their expenditure on one another 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. This 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 question is pertinent to the 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 and environmental commodity accounts, demonstrated in Chapter 3 and discussed in Sections 2.2.2 and 3.4, illustrate why this thesis research 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 a arguable a source of ignorance, calling into question whether the latter really ‘drives’ the former. Ignorance is also present 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. The unbounded nature of uncertainty is an important, but under emphasised, quality of modelling complex systems (Brown, 2004). The completeness and validity of knowledge related to the WEL system therefore not only relates to the limitations of approaches used to study it, but also the unknown and potential large ‘opportunity cost’ of those approaches, perspectives, and interpretations which are overlooked in the process.

7.4 Future avenues for nexus assessment

Several lines of future research inquiry emerge from the analysis in this thesis, which have the potential to improve understanding of the pressures across the WEL system. This section identifies three main areas where further development is needed: bridging spatial scales of resource use, improving the sectoral resolution of nexus assessment, bridging temporal scales of resource use, and communicating threats across the nexus.

7.4.1 Bridging spatial scales of resource use

A major challenge to tracing pathways of resource use within the world economy is to understand how resource-related pressures are transmitted through consumption and production systems between local, national, and global scales. At present, MRIO *and* MFA databases do not capture the heterogeneity of resource use, production and consumption patterns at a sub-national scale. This limits the spatial resolution of resource footprinting analysis to country-specific interactions. As a result, economy-wide resource footprinting is unable to pin-point the exact production locations and resource use (e.g. water basin, energy facility, or farm) associated with consumption activities, nor can it unpack the composition of national consumption responsible (e.g. between municipalities, rural areas and across socio-demographic groups) (Dietzenbacher et al., 2013a). Such aggregation issues disguise policy entry points at both the demand-side management and supply-side management of sustainable resource use. However, in recent years two approaches have emerged to help bridge the different spatial scales of resource use. These can be distinguished as data-driven and model-driven approaches to down-scaling resource footprint assessment. The data-driven approach to high-resolution footprinting attempts to link sub-national production, trade and resource use data to MRIO databases to extend their spatial scope of analysis. This is exemplified in case studies of Brazil (Croft et al., 2018; Flach et al., 2016; Godar et al., 2015), China (Dong et al., 2014; Guan & Hubacek, 2007; Jiang et al., 2015), and Indonesia (Faturay et al., 2017). Although detailed, such an approach is costly, in terms of processing data. Moreover, as Wiedmann & Lenzen (2018) note, it is not likely that we will see increased sub-national data collection and reporting for the purpose of MRIOA analysis in the near-term, a point repeated in a review by Dietzenbacher et al. (2013a) on the future of input-output economics in the next 25 years. Consequently, a data-driven approach does not offer a practical approach to improving the sub-national detail of all countries and sectors within MRIO databases. In contrast, the linkage of high resolution geo-referenced environmental datasets to MRIO consumption sectors via concatenating sector-specific environmental risk maps to MRIO production sectors offers a disciplined methodological approach to distinguish the severity and location of country and sector impacts on the global environment at a sub-national scale. Such a model-driven approach has enabled spatially explicit mapping of countries in terms of greenhouse gas emissions (Kanemoto et al., 2016), biodiversity (Moran & Kanemoto, 2017), and air pollution (Moran & Kanemoto, 2016) and is likely to be extended to water, energy and land for the Eora (2019) database in coming years as part of a project at the Research Institute for Humanity and Nature in Japan (RIHN, 2019).

7.4.2 Improving the sectoral resolution of nexus assessment

The sectoral resolution of MRIO data is a major constraint to the reliability and practical application of resource footprint analysis in this thesis. In terms of reliability, the level of sectoral aggregation within Eora (2019) directly affects the calculation of (i) interdependencies between sectors, (ii) resource use multipliers, and (iii) resultant resource footprints (de Koning et al., 2015). Although the most detailed version of the Eora (2019) database is used for analysis, 119 of the 189 countries analysed report data for only 26 sectors. However, it is important to note that these 119 countries constitute only 12% of the global water footprint, 8% of the global energy footprint, and 13.7% of the global land footprint. Ongoing improvements to the scope and frequency of national reporting within the UN (2014) System of Economic and Environmental Accounting stand to improve the sectoral resolution of MRIO data. However, physical environmental and commodity accounts are likely to remain more detailed in terms of product-level coverage when compare with MRIO data. Chapter 3 exemplifies the additional richness of such data and analysis at this level in its use of a crop-specific resource intensity coefficient when compared with the sector-averaged (i.e. multi-crop) resource intensity coefficients used in MRIOA. Attempts to integrate physical and financial data within resource footprinting analysis represents an opportunity to improve the sectoral resolution of MRIOA and the supply chain coverage of MFA. The recent development of several hybridised physical-financial models, such as *The Footprint Family of Indicators* (Ewing et al., 2012; Galli et al., 2012), the *Food and Agriculture Biomass Input–Output (FABIO) Model* (Bruckner et al., 2019), *IOTA* (Croft et al., 2018), and *SEI-PCS* (Godar et al., 2015) represent a promising sign within this context.

7.4.3 Forecasting pathways of resource use

The ability to forecast resource use is essential to understand how pressures across the WEL system might change over time and in response to different policy measures. Although using MRIO databases to simulate future and alternative resource-use scenarios is technically possible it remains undeveloped in resource footprinting scholarship owing to several complexities. First, projecting MRIO databases involves a comprehensive set of predictions surrounding technological development, consumption patterns, population growth, trade, and employment in individual countries which are not always readily available (Miller & Blair, 2009). Second, perturbing MRIO databases is computationally costly as it involves frequent re-calibration of large matrices and the associated elements of the Leontief demand-pull model. Third, since MRIOA captures resource flows and not stocks, constraints need to be added which reflect thresholds of sustainable resource extraction to ensure final consumption can be satisfied; these are scarcely documented for most countries. Notwithstanding these challenges, forecasting pathways of MRIOA has already generated rich insights into (i) the limits of efficiency improvements within the economy (Wiebe et al., 2019), (ii) the possible rebound effects of consumption-based behaviour change (Wood et al., 2017), and (iii) future trade-related resource use between economies (Wang et al., 2019). Moreover, techniques to predict resource flows across resource use networks based on historical data such as those proposed by Tuninetti et al. (2017) in relation to virtual water and Wang et al. (2019) for carbon emissions embodied in trade, can help to ensure these forecasts are informed by past observations. Techniques to deal with the computational challenges of MRIO database manipulation (*cf* Geschke et al., 2019; Lenzen, 2019; Wenz et al., 2015), also pave the way for development in this area. However, greater attention to the development of models which are capable of dynamically modelling socio-ecological systems are also needed to forecast realistic pathways of future resource use (Liu et al., 2015).

7.4.4 Communicating threats across the WEL system

A secondary challenge when modelling pressures across the WEL system is communicating the findings of their analysis in an accessible and actionable way. The sheer scale of MRIO databases, consisting of billions of data points, demand significant post-processing of analysis to produce meaningful observations about country and sector influence on water, energy and land resources. However, there is a tendency, when faced with such complexity, for conventional resource footprinting analysis to over-aggregate and under-interpret the rich information arising from MRIOA in a manner which disguises important features of country and sector resource use pathways. This thesis illustrates how country and sector resource footprints can be unpacked, spatially (Chapters 3 and 4), sectorally (Chapter 5) and in relation to their supply network (Chapter 6), to reveal the sources of pressures across the WEL system. The role of indicators and data visualisation emerged from this analysis as two main priorities for the effective communication of threats across the WEL system. Indicators allow for filtering of important information around country and sector resource footprints such as high risk resource use, common resource origins, and their supply chain scope. Meanwhile, data visualisation enables communication of large, multi-dimensional data in an straightforward and engaging way.

Several promising avenues of future development of indicators and data visualisation have been identified, but could not be explored within the time constraints of this thesis research. 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 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), betweeness 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. Betweeness 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; Kanemoto et al., 2019; Li et al., 2017) and water use (D'Odorico et al., 2012; Konar et al., 2011; Tian et al., 2018).

In terms of data visualisation, other potentially useful formats and techniques of presenting resource flows include Sankey diagrams and network graphs. Sankey diagrams show the flow of natural resources from their extraction through transformations to final services within a given system (Lupton & Allwood, 2016). Such a representation of resource systems allows straightforward interpretation of the major sources of supply and demand. Sankey diagrams are most instructive when used to convey a limited number of input-output relationships (≈ 50) within a resource use network and therefore would demand an aggregated view of the data within this thesis. Specific applications of Sankey diagram might include analysis of global regions (Bajželj & Richards, 2014), individual countries (Curmi et al., 2013b), or single sectors (Cullen et al., 2012).

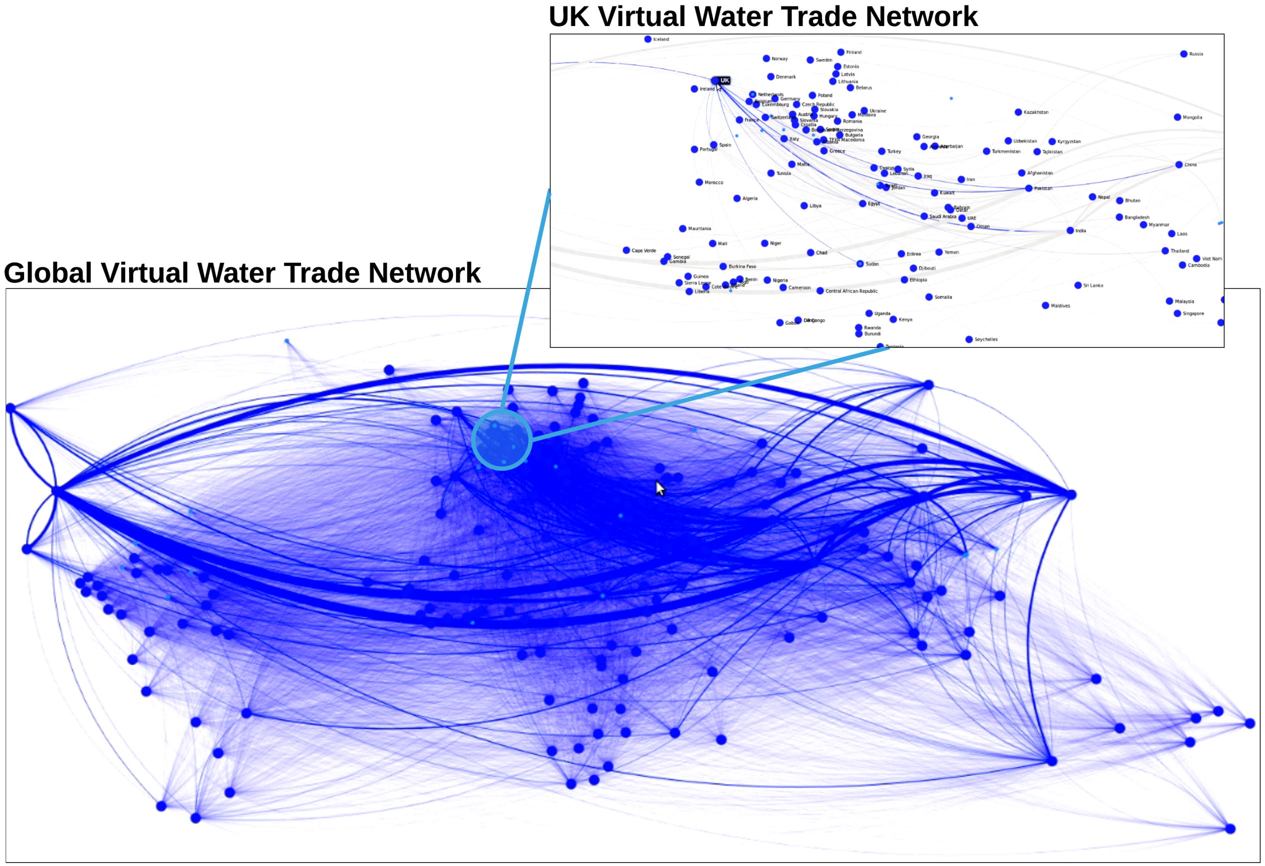

Fig. 7.2 Network perspective of global virtual water trade

Network diagram depicting the global virtual blue water network and the UK's trade-related water dependence in 2015 based on analysis of the Eora (2019) model in this thesis. This is produced using by converting the 189x189 matrix of intra-country (diagonal values) blue water demand to an adjacency list (of 35721 rows) summarising these interdependencies in terms of (i) source, (ii) destination and (iii) weight (e.g. 5Mm^3). This adjacency list was formatted for interpretation by Gephi^{TM}, a network visualisation platform, and hosted interactively using a plugin (Sigma.js) developed by the Oxford Internet Institute at the University of Oxford (OII, 2012).

In contrast, network diagrams can be used to represent more fully the complex web of resource dependencies which connect countries and sectors. A resource use network diagram constitutes (i) nodes which can represent regions, countries or sectors, (ii) links which describe the directionality of their relationships and (iii) weights which describe the magnitude of these relationships. Due to the matrix structure of MRIOA it is straightforward to depict country and sector resource use pathways in networks. Figure 7.2 illustrates the virtual blue water trade between the countries in the Eora (2019) database in 2015. The advantage of network analysis is that the network can be geo-referenced to sets of country and region coordinates, producing an world map of influence across global resource systems which can be easily interpreted.

Invariably, there is a need for interactive visualisation of MRIO data and nexus analysis where the nested structure of results benefits from being viewed at various levels of aggregation (Vivanco et al., 2019). A promising sign within this context is the recent development of several interactive platforms to visualise country and sector footprints, such as *The Virtual MRIO lab* (Geschke & Hadjikakou, 2017), *The Trase Tool* (Croft et al., 2018), and *The Environmental Footprint Explorer* (NTNU, 2019). Crucially, however, analysts need to better connect the communication of MRIOA and nexus analysis with a deeper understanding of end users (e.g. government, business and civil society) and how they interpret data.

7.5 Managing the water-energy-land nexus

The practical requirements for implementing nexus-based 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 nexus 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 exists 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 administrations 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 nexus and how they can be overcome (Lele et al., 2013). The vast literature on environmental policy integration (Nilsson et al., 2016; Nilsson & Persson, 2003; Nilsson & Eckerberg, 2009), and the growing number of contexts in which nexus-based governance is being evaluated and operationalised (*cf* Biba, 2016; Boas et al., 2016; Hagemann & Kirschke, 2017; Larcom & van Gevelt, 2017; Mercure et al., 2019), provide a reference for such evaluation. Although highly important, the scope of this thesis does not lend itself to the close examination of governance principles for integrated management of the WEL system. Because of its emphasis on the analytical issues themselves; a study of governance would be a distinct field of enquiry methodologically and conceptually.

The macro scale at which analysis within this thesis has been undertaken, given the data available, does not directly map onto a set of effective actors or scales of management. In practice, the level of coordination, power sharing and information exchange which would be necessary for the management of global value chains varies at the scale of individual businesses and their supply chains (Emmett & Crocker, 2006). Consequently, the ability of national governments or even sectors to identify, engage with, and regulate suppliers; and effectively codify sustainable production practices is limited without collective effort (Gereffi et al., 2005). Indeed, suppliers are governed by both public and private authority at multiple scales and levels, and under multilateral and normative objectives. This multi-polar nature of supply chain governance, combined with the complex and fragmented organisation of suppliers, creates no obvious entry point for the management of pressures within 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 inquiry with few practical recommendations for its governance (Stirling, 2015). Although a discussion of governance at the scope of this thesis is untenable, it is useful to reflect on pertinent policy questions and priorities which emerge from its analysis. These concern (i) reducing risks across the WEL system (ii) managing trade-related resource use and (iii) achieving integrated management of water, energy and land use.

The findings of analysis within this thesis reinforce the need for patterns of consumption, production and trade patterns compatible with the sustainable use of water, energy and land resources. This is exemplified most clearly by the scale of high risk resource use embodied in national consumption (Section 4.3.1) and sectoral demand (Section 5.4.1) and the concentration of resource dependence in specific countries (Section 4.3.2). However, the interconnected nature of resource pathways, also highlighted by this thesis, suggests an equally complex landscape for managing pressures across the WEL system. Linking national consumption to source, in Chapter 4, suggests countries and sectors are highly exposed, directly (via domestic production) and indirectly (via imports), to over-exploited, insecure, and degraded water, energy, and land resources. The unsustainable nature of resource dependence across the WEL system represents a source of risk for the various activities it supports (e.g. food supply, infrastructure, and services). Hence, it is necessary to examine what de-risking the WEL system might involve. This can be unpacked by exploring two questions: (i) the de-risking of what to what? and (ii) the de-risking for whom by whom? The highly contested nature of these questions can be approached through multiple lenses.

The decision to *model* the WEL system acts to reinforce the already dominant paradigm of quantitative assessment in the study and management of natural resource systems (Stirling, 2015). By framing the problem space of natural resource use in purely numeric terms, there is a propensity for this thesis to encourage an apolitical view of the drivers, consequences and possible remedies linked to overexploitation of water, energy and land resources. For example, MRIOA does not readily expose the links between inequality and resource use which derive from uneven historical development within and between countries and regions of the world economy. Moreover, the lock-in of countries to unsustainable patterns of resource extraction is not merely a consequence of societal choice but a product of national and international policy regimes which often have benefited from the exploitation of natural resources without direct exposure to its consequences (Allouche et al., 2015; Siegfried et al., 2008; Srivastava et al., 2017). Meanwhile, the balanced formula and data in IOA appeals to the use of economic optimisation techniques to identify consumption, production, and trade patterns which minimise resource use. Such optimised scenarios might assume unrealistic constraints on the reorganisation of supply chains, sourcing structures, and the social and political consequences of their recommendations. Consequently, the structure of MRIOA and its relationship to problem framing and knowledge production must be critically analysed and held in simultaneous view with other perspectives, both quantitative and qualitative, when studying challenges across the WEL system. This thesis offers one perspective to de-risking the WEL system. By exposing differences between the scale and severity of country and sector resource footprints the analysis in this thesis can help to redress notions of responsibility within the context of natural resource management.

A basic perspective which could be explored involves distinguishing basic and non-basic human needs. For example, sustenance might be categorised as a basic human need where consumption needs to be maintained, whereas air travel, consumption of animal products, or purchase of luxury clothing might represent activities where demand can be reduced without undermining human rights or well-being. Given the growing evidence suggesting that absolute decoupling of resource use from economic growth is not achievable with continued levels of consumption and materialism (Hickel & Kallis, 2019; Krausmann et al., 2017; UNEP, 2011; Ward et al., 2016), it appears that demand-side management is a crucial part of any strategy designed to reduce pressures and risk across the WEL system. Equally, as demonstrated by the shared nature of country and sector resource supply in Section 4.3.2, managing resource pressures at their source, through efficiency measures and limits on resource extraction, has the potential to improve the sustainability and resilience of the entire WEL system, for all actors. Due to the potential positive spillover effects delivered to downstream supply chain actors, the costs of supply-side measures might arguably be shared across production and consumption systems.

Mechanisms for managing resource use embodied in the international trade system have received little attention when viewed within the context of their significance. In particular, trade agreements, which strongly shape the international trade network and the conditions under which goods and services are produced, are scarcely discussed as an important, legal instrument for managing pressures on natural resources. Indeed, at the time of writing, no comprehensive review of such provisions has been identified. A review of trade agreements between 2008 and 2018, reported in Taherzadeh (2019a) and Taherzadeh (2019b), was completed as part of this thesis research to examine the state of environmental, social and economic provisions in bilateral and multilateral agreements between 2008-2018 in relation to the UN Sustainable Development Goals (SDGs). Of a total of 105 agreements analysed, 23 (22%) of trade agreements were found to contain a high level of provisions for the SDGs; 23 medium; 31 low; and, 27 featured no provisions (Taherzadeh, 2019a). This review highlighted the significant potential for improving environmental provisions in trade agreements to help facilitate sustainable resource use embodied in trade. Several existing provisions were identified in specific cases. For example, the *EU-Eastern and South African States (ESA)* trade agreement (Article 50) commits members to cooperation to ensure sustainable utilisation of transboundary water resources and capacity building with regard to water management. The *EU-Canada* trade agreement requires its members to "*pay special attention to facilitating the removal of obstacles to trade or investment in goods and services of particular relevance for climate change mitigation and in particular trade or investment in renewable energy goods and related services*". The *European Free Trade Association (EFTA)-Central America* trade agreement (Article 9.8) encourages its member to improve forest law and promote trade in legal and sustainable fores-based products. At present, this review suggests that trade, through deregulation, currently prioritises investment rights to natural resources over investment responsibility for their sustainable management. Consequently, the inclusion and strengthening of environmental provisions appears to be an important, under-utilised mechanism for management of transboundary impacts of national consumption on water, energy and land resources. Such a focus is extremely timely within the ongoing negotiation of environmental standards in the UK long-term relationship with the EU. Notwithstanding the importance of this management area, a more detailed assessment of the comparative advantage of international trade relationships is necessary to understand whether the globalisation of country and sector supply networks is necessary and logical within the context of national resource availability.

WEF nexus analysis assigns primary importance to interdependent pathways of resource use within the food system: food-energy, energy-water, food-water. Although this adds a new vantage point to assess the environmental impacts of food systems, these feedbacks often do not constitute major pathways of resource use (Bijl et al., 2018; Vivanco et al., 2018b; White et al., 2018). By definition, WEF-centric analysis overlooks competition for water, energy, and land resources with other services (e.g. construction, electronic, and clothing) and priorities (e.g. environmental conservation and urban development). In some cases, non-food sectors pose a more acute burden than food-related demand on water, energy and land resources (see Chapter 5). A more comprehensive multi-sectoral analysis of WEL system, undertaken within this thesis, identifies countries, sectors, and supply chains critical to the promotion of integrated management of water, energy, land resources. Despite a growing number of studies on the WEF nexus, we still lack a foundational understanding of these priority areas. Nexus analysis undertaken across all aspects of human activity can also help to inform more coherent, comprehensive, and transformative pathways for securing basic social needs within planetary boundaries (Raworth, 2017). The speed, scale, and severity of resource depletion and environmental change requires no less than a systemic approach; it is not clear that WEF-nexus analysis provides this yet.

In contrast to other commentators (Wichelns, 2017), this thesis does not question the principal need for nexus-style assessment. As development begins to outstrip the limited capacities of multiple environmental systems (water, land, climate, ecosystems and beyond), integrated appraisal of policy measures appears increasingly necessary. Instead, this thesis argues that WEF-centric analysis fails to capture fully the many drivers of resource use within production and consumption systems. While effective management of the WEF linkages might promote sustainable allocation of natural resources, it does not necessarily guarantee it. As a rule of thumb, boundaries of nexus analysis and governance should be informed by a comprehensive understanding of the total environmental burden of human activity as it emerges from analysis of the data. By contrast current analysis of the WEF nexus tries to set these boundaries *a priori*. This thesis research calls for a refocusing of nexus assessment to encompass the cross-sectoral and multi-scale nature of the pressures and risks across the WEL system. Without a systemic approach, the value of the nexus concept to integrated environmental management remains unclear. Only when we zoom out from the WEF nexus can we begin to identify the opportunities for joined-up thinking in our complex and changing world.

Over the next two decades demand for water, energy and land resources is forecast to increase, while our ability to meet growing resource needs is likely to be reduced by climate change, resource exhaustion, and environmental pollution (IPCC, 2014). Decisions taken now in relation to water, energy and land resources will strengthen or weaken the ability of humanity to meet its basic needs. The need for a systemic analysis of the world economy, like the one taken in this thesis, is essential if we are to fully comprehend the scale of this crisis and the necessary scale of our response.

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Appendix A

Programming code for model

The programming code within this section documents all modelling procedures associated with analysis within this thesis. To avoid repetition, programming code is provided for a sub-set of analysis in each chapter, but is capable of being scaled by aggregating and disaggregating between country, region or sector scales. The computational requirements of these procedures can be found in Chapter 2 Section 2.2.8.

Resource risk footprint calculation using MRIOA (country example)

```
y= ‘Y1990’;‘Y1991’;‘Y1992’;‘Y1993’;‘Y1994’;‘Y1995’;‘Y1996’;‘Y1997’;‘Y1998’;‘Y1999’;‘Y2000’;‘Y2001’;‘Y2002’;‘Y2003’;‘Y2004’;‘Y2005’;‘Y2006’;‘Y2007’;‘Y2008’;‘Y2009’;‘Y2010’;‘Y2011’;‘Y2012’;‘Y2013’;‘Y2014’;‘Y2015’}; % load year labels

cname=readtable(‘/home/CountryNames.txt’,‘Delimiter’,‘"’,‘ReadVariableNames’,false); % Load country names
cname.Properties.VariableNames{1} = ‘Countries’; % rename heading
cname=table2cell(cname); % convert table to array
cname=strrep(cname," ",""); % concatenate spaces in cell name to use as variables

ii=26 % example for 2015
% MRIO Component Load and Calculations
T=load([‘/home/T_’ num2str(yr{ii}) ‘.txt’]); % load financial transactions matrix
T=T(1:14838,1:14838);
FD=load([‘/home/FD_’ num2str(yr{ii}) ‘.txt’]); % load financial demand matrix
```

```
FD=FD(1:14838,1:1140);
Q=load(['/home/Q_' num2str(yr{ii}) '.txt']); % load environmental
   ↪ accounts

  for i=1:189;
            j=((i-1)*6)+1;
            k=i*6;
            fd(:,i)=sum(FD(:,j:k),2);
  end

Q=Q(1:2720,1:14838);
x=sum([T FD],2); % output = intermediate + final demand
x(x==0) = 0.000000001; % ensure no non-zero values to enable matrix
   ↪ inversion
BIGX = repmat(x',14838,1); % generate matrix with repeated output
   ↪ values
A=T./BIGX; % generate technical coefficients matrix (i.e. production
   ↪ recipe)
L=inv(eye(14838)-A); % calculate Leontief Inverse Matrix

% Calculating direct and indirect environmental footprints
Wv=(Q(2500:2501,:)); % load blue and green water vector
Wv=sum(Wv); % calculate combined blue and green water vector
WI=Wv*inv(diag(x)); % direct water intensity per $ output
Ev=(Q(1:9,:)); % load primary energy supply vector
Ev=sum(Ev);
EI=Ev*inv(diag(x)); % direct energy intensity per $ output
Lv=(Q(2080:2251,:)); % load land area vector
Lv=sum(Lv); % aggregate land area vector for all agricultural
   ↪ commodities
LI=Lv*inv(diag(x)); % direct land intensity per $ output

clear T FD Q x BIGX A % clear variables that are not needed to reduce
   ↪  memory requirement

% Calculation of risk-partitioned resource footprints
r={'W','E','L'}; % index to distinguish WEL accounts
part={'F','L','M','H','NotClassified'}; % risk partitions:
   ↪   N  o  n  e  lowMediumHighUnclassified  to calculate
   ↪ aggregate country resource footprints
```

```
partm={‘Fm’,‘Lm’,‘Mm’,‘Hm’,‘NotClassifiedm’}; % risk partitions to
   ↪ store disaggregated country-country resource dependencies
   ↪ matrix at given risk level
FP=categorical({‘Water’,‘Energy’,‘Land’});

Rs=readtable(‘/home/ResourceSecurityRanks.csv’); % load raw resource
   ↪ index data for water, energy and land
Rs=table2array(Rs(:,2:4)); % convert table to array
Rs=table2array(Rs(:,2:4));

for i=1:3;
    for j=1:189;
        RsNorm.(r{i})(1:189,1)=1; % compute no filter (i.e. to
   ↪ represent all resource flows)
        vec=isnan(Rs(1:189,i)); % compute ‘Unclassified’ filter
        RsNorm.(r{i})(:,5)=vec; % add unclassified filter

        for k=1:3; % risk filters: Low->Medium->High
            Max=max(Rs(:,i));
            idx=Rs(j,i)>=(Max*k/3.00-Max/3.00) & Rs(j,i)<=(Max*k)
   ↪ /3.00; % normalise raw resource index data and partition by
   ↪ thirds
            RsNorm.(r{i})(j,k+1)=idx;
        end
    end
end

for c=1:189 % Country loop
  WF=abs(diag(WI)*L*diag(fd(:,c))); % calculate disaggregated water
   ↪ footprint for country   c
  EF=abs(diag(EI)*L*diag(fd(:,c))); % calculate disaggregated energy
   ↪ footprint for country   c
  LF=abs(diag(LI)*L*diag(fd(:,c))); % calculate disaggregated land
   ↪ footprint for country   c

% collapse 14838x14838 sector-sector resource requirements matrices
   ↪ to 189x189 country-country equivalents
for i=1:189;
  for n=1:189;
```

```
      j = from(i):to(i); % where from and to index the
   ↪ position of first and last sectors for each country within the
   ↪ Eora database
        k = from(n):to(n);
        WFcountry.(cname{c})(n,i)=sum(sum(abs(WF(k,j))));
        EFcountry.(cname{c})(n,i)=sum(sum(abs(EF(k,j))));
        LFcountry.(cname{c})(n,i)=sum(sum(abs(LF(k,j))));
  end
end

for k=1:5;
% calculate disaggregated country resource risk footprints
  R.WF.(cname{c}).(partm{k})=WFcountry.(cname{c}).*(RsNorm.W(:,k)); %
  R.EF.(cname{c}).(partm{k})=EFcountry.(cname{c}).*(RsNorm.E(:,k));
  R.LF.(cname{c}).(partm{k})=LFcountry.(cname{c}).*(RsNorm.L(:,k));
% calculate single value country risk footprints
  R.WF.(cname{c}).(part{k})=sum((sum((WFcountry.(cname{c}).*(RsNorm.W
   ↪ (:,k))))));
  R.EF.(cname{c}).(part{k})=sum((sum((EFcountry.(cname{c}).*(RsNorm.E
   ↪ (:,k))))));
  R.LF.(cname{c}).(part{k})=sum((sum((LFcountry.(cname{c}).*(RsNorm.L
   ↪ (:,k))))));
  end
end

% Equivalent to above for creating filters for risk analysis of
   ↪ asymmetric sectors in the Eora database. Follow procedure above
   ↪  to calculate sectoral risk-based resource footprints,
   ↪ substituting WF, EF and LF for resource footprints calculated
   ↪ with total final demand vector: FD=sum(FD,2) instead of
for fp=1:3 % risk filters: Low->Medium->High
    for i=1:189 % country loop
        for k=1:5 % risk filters: None->low->Medium->High->
   ↪ Unclassified
                for rng=from(i):to(i) % where ‘From’ and ‘to’
   ↪ represent start and finish index of country sectors in the Eora
   ↪  database
                RsNormSec.(r{fp})(rng,k)=repmat(RsNorm.(r{fp})(i,k),
   ↪ length(rng),1); % scale country risk filters by Eora sectors
                end
```

```
        end

    end
end
```

Example of regional-level resource footprint analysis

```
Regions={‘TOT’,‘NAF’,‘EAF’,‘MAF’,‘SAF’,‘WAF’,‘CAR’,‘CAM’,‘SAM’,‘NAM
   ↪ ’,‘CAS’,‘EAS’,‘SEA’,‘SAS’,‘WAS’,‘EEU’,‘NEU’,‘SEU’,‘WEU’,‘OCE’}

envrow={’2500:2501’;’1:9’;’2080:2251’} % water, energy and land
   ↪ vector indexes in the Eora database

for FP=1:3 % loop for water, energy and land
for i=1:20 % load for global total + 19 global regions
  Sector.(fp{FP}).(Regions{i})=diag((sum(Q(cell2mat(envrow(FP)),:))))
   ↪ *L*diag(sum(Y.(Regions{i}),2)); % calculate regional resource
   ↪ footprints at sector resolution

for m=1:189 % evaluate the distribution of regional resource demand
   ↪ at a country-level
    for n=1:189
      j = from(m):to(m); % where ‘From’ and ‘to’ represent start and
   ↪ finish index of country sectors in the Eora database
      k = from(n):to(n);
      Country.(fp{FP}).(Regions{i})(n,m)=sum(sum(abs(Sector.(fp{FP})
   ↪ .(Regions{i})(k,j))));
    end
end

for k=1:20 % rearrange countries by region in regional resource
   ↪ requirements matrix
    for n=1:189
        Region.(fp{FP}).(Regions{i})(:, n)=(Country.(fp{FP}).(Regions
   ↪ {i})(:,countryindex(k))); % where country index is a 1x189
   ↪ vector of values to index countries to regional groupings
    end
end

    for r=1:20 % calculate regional resource requirement by region
         RegionAggregate.(fp{FP}).(Regions{i})(r,1)=(sum(sum((Region
   ↪ .(fp{FP}).(Regions{i} (:,jindex(r):kindex(r)))))); % where
```

```
   ↪ jindex and kindex set the range (start to finish)
   ↪ of countries in each region
    end

      RegionalMatrix.(fp{FP})(:,i)=RegionAggregate.(fp{FP}).(Regions{
   ↪ i})(:,1) % produce a regional level matrix of resource
   ↪ requirements for all regions

end
end

% calculate the regional distribution of country resource footprints
   ↪ and risk
for c=1:189 % loop by country
for i=1:20; % loop by region
        range=(jindex(i):kindex(i));
        idx=countryindex(range);

        for j=1:sum(idx>0) % loop by number of countries in region
            ConWFregdecomposed(c,i)=sum(sum(WFcountry.(cname{c})(idx
   ↪ ,:)));
            ConEFregdecomposed(c,i)=sum(sum(EFcountry.(cname{c})(idx
   ↪ ,:)));
            ConLFregdecomposed(c,i)=sum(sum(LFcountry.(cname{c})(idx
   ↪ ,:)));

            ConWFriskregdecomposed(c,i)=sum(sum(WFcountry.(cname{c})(
   ↪ idx,:).*RsNorm.W(idx,4)));
            ConEFriskregdecomposed(c,i)=sum(sum(EFcountry.(cname{c})(
   ↪ idx,:).*RsNorm.E(idx,4)));
            ConLFriskregdecomposed(c,i)=sum(sum(LFcountry.(cname{c})(
   ↪ idx,:).*RsNorm.L(idx,4)));

            end
end
end
```

Boundary analysis of resource footprints for domestic food and non-food related sectors

```
% Load and calculate MRIOA components, as documented in Appendix A: ‘
   ↪ Resource risk footprint calculation using MRIOA’

for i=1:189 % loop by country
     j=from(i):to(i); % where ‘From’ and ‘to’ represent start and
   ↪ finish index of country sectors in the Eora database
% calculate fully disaggregated resource footprints
    WFFP=abs(diag(WI)*L*diag(fd(:,i)));  % calculate disaggregated
   ↪ water footprint for country    c
    EFFP=abs(diag(EI)*L*diag(fd(:,i))); % calculate disaggregated
   ↪ energy footprint for country    c
    LFFP=abs(diag(LI)*L*diag(fd(:,i))); % calculate disaggregated
   ↪ land footprint for country    c

% calculate aggregated global resource footprints (1x14838) to assess
   ↪  the global resource footprint of country sectors
    WF(:,i)=sum(WFFP)';
    EF(:,i)=sum(EFFP)';
    LF(:,i)=sum(LFFP)';

Wfdom=WFFP(j,j); % isolate the domestic water footprint of domestic
   ↪ sectors
Wfbs(i,1)=100*sum(sum(WFdom(:,fsec(j)>0)))./sum(sum(WFFP)); %
   ↪ calculate the contribution of domestic food-related sectors to
   ↪ a countrys global water footprint. *where fsec is a vector
   ↪ mask of ones and zeros which filters food-related sectors*
Wfbs(i,2)=100*sum(sum(WFdom(:,isnan(fsec(j))))))./sum(sum(WFFP)); %
   ↪ calculate the contribution of domestic non-food sectors to a
   ↪ countrys global water footprint
Wfbsrisk(i,1)=100*sum(sum(WFdom(:,fsec(j)>0).*RsNormSec.W(j,4)))./sum
   ↪ (sum(WFFP.*RsNormSec.W(:,4))); % calculate the contribution of
   ↪ domestic food-related sectors to a countrys global high risk
   ↪  water footprint
Wfbsrisk(i,2)=100*sum(sum(WFdom(:,isnan(fsec(j))).*RsNormSec.W(j,4)))
   ↪ ./sum(sum(WFFP.*RsNormSec.W(:,4))); % calculate the
   ↪ contribution of domestic non-food sectors to a countrys
   ↪ global high risk water footprint

%% as above for energy (‘EF ) and land (‘LF’)
```

```
Efdom=EFFP(j,j);
EFbs(i,1)=100*sum(sum(EFdom(:,fsec(j)>0)))./sum(sum(EFFP));
EFbs(i,2)=100*sum(sum(EFdom(:,isnan(fsec(j)))))./sum(sum(EFFP));
EFbsrisk(i,1)=100*sum(sum(EFdom(:,fsec(j)>0).*RsNormSec.W(j,4)))./sum
    ↪ (sum(EFFP.*RsNormSec.W(:,4)));
EFbsrisk(i,2)=100*sum(sum(EFdom(:,isnan(fsec(j))).*RsNormSec.W(j,4)))
    ↪ ./sum(sum(EFFP.*RsNormSec.W(:,4)));

LFdom=LFFP(j,j);
LFbs(i,1)=100*sum(sum(LFdom(:,fsec(j)>0)))./sum(sum(LFFP));
LFbs(i,2)=100*sum(sum(LFdom(:,isnan(fsec(j)))))./sum(sum(LFFP));
LFbsrisk(i,1)=100*sum(sum(LFdom(:,fsec(j)>0).*RsNormSec.W(j,4)))./sum
    ↪ (sum(LFFP.*RsNormSec.W(:,4)));
LFbsrisk(i,2)=100*sum(sum(LFdom(:,isnan(fsec(j))).*RsNormSec.W(j,4)))
    ↪ ./sum(sum(LFFP.*RsNormSec.W(:,4)));

end
```

Example of Production Layer Decomposition

```
% Load and calculate MRIOA components, as documented in Appendix A: ‘
    ↪ Resource risk footprint calculation using MRIOA’
for c=1:189 % calculate country overall resource footprints (See REF)
    ↪  and high risk resource footprints (see REF)
     WF=sum(sum(abs(diag(WI)*L*diag(fd(:,c)))));
     WFr=sum(sum(abs(diag(WI)*L*diag(fd(:,c))).*RsNormSec.W(:,4)));

     EF=sum(sum(abs(diag(EI)*L*diag(fd(:,c)))));
     EFr=sum(sum(abs(diag(EI)*L*diag(fd(:,c))).*RsNormSec.W(:,4)));

     LF=sum(sum(abs(diag(LI)*L*diag(fd(:,c)))));
     LFr=sum(sum(abs(diag(LI)*L*diag(fd(:,c))).*RsNormSec.W(:,4)));

for    l=1:11 % Define number of production levels for Production
    ↪ Layer Decomposition
    WFsum(l,c)=100*sum(sum((diag(WI)*(A^(l-1))*diag(fd(:,c)))))./WF %
    ↪  calculate percent contribution of production layer to overall
    ↪ water footprint of country ‘C’
    WFrisk(l,c)=100*sum(sum((diag(WI)*(A^(l-1))*diag(fd(:,c)))).*
    ↪ RsNormSec.W(:,4))./WFr % calculate percent contribution of
    ↪ production layer to high risk water footprint of country ‘C’
```

```

    EFsum(l,c)=100*sum(sum((diag(EI)*(A^(l-1))*diag(fd(:,c))))./EF %
  ↪  calculate percent contribution of production layer to overall
  ↪ energy footprint of country ‘C’
    EFrisk(l,c)=100*sum(sum((diag(EI)*(A^(l-1))*diag(fd(:,c)))).*
  ↪ RsNormSec.E(:,4))./EFr % calculate percent contribution of
  ↪ production layer to high risk energy footprint of country ‘C’

    LFsum(l,c)=100*sum(sum((diag(LI)*(A^(l-1))*diag(fd(:,c))))./LF %
  ↪  calculate percent contribution of production layer to overall
  ↪ land footprint of country ‘C’
    LFrisk(l,c)=100*sum(sum((diag(LI)*(A^(l-1))*diag(fd(:,c)))).*
  ↪ RsNormSec.L(:,4))./LFr % calculate percent contribution of
  ↪ production layer to high risk land footprint of country ‘C’
end
end
```