An Overview of Recent Developments of Multi-Regional Input-Output Tables and Extensions for Consumption-based Accounting

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Abstract

The use of global, multi-regional input-output (MRIO) analysis for consumption-based (footprint) accounting has expanded significantly over the last decade. Most of the global studies on environmental and social impacts associated with consumption or embodied in international trade would not have been possible without the rapid development of extended MRIO databases. Here we present an overview of the developments in the field of MRIO analysis, in particular as applied to consumption-based environmental and social footprints. We first provide a discussion of research published on various global MRIO databases in existence and the differences between them, before focussing on the virtual laboratory computing infrastructure for potentially making MRIO databases more accessible for collaborative research, and also for supporting greater sectoral and regional detail. We discuss work that includes a broader range of extensions, in particular the inclusion of social indicators in consumption-based accounting. We conclude by discussing the future need for the development of detailed nested MRIO tables for investigating linkages between regions of different countries, and the applications of the rapidly growing field of global MRIO analysis for assessing a country's performance towards the United Nations Sustainable Development Goals.

Keywords: consumption, input-output analysis, social footprints, virtual laboratory, sustainability assessment.

1 Introduction

In 1776 Adam Smith[1] stated that "*Consumption is the sole end and purpose of all production*", concluding that "*… the interest of the producer ought to be attended to, only so far as it may be necessary for promoting that of the consumer.*" Even though the world has changed dramatically since, and globalisation has increased the physical separation between consumers and producers, there is an inextricable economic link between consumption and production and the first part of Smith's statement is still valid today. Its interpretation, however, has changed in a world that is increasingly becoming concerned about the environmental and social impacts of global economic growth (Costanza et al. 2014). In modern times scholars have directed their attention to the question of who is responsible for these impacts and how the negative impacts can be mitigated (Jackson 2011; Jackson 2016). Understanding these impacts is important not only for consumers and policy makers, but also producers as they have to respond to information demands from extended producer responsibility, detailed supply chain analysis and markets.

There exists literature on this topic. In 2009, Wiedmann reviewed the use of multi-regional input-output (MRIO) analysis to analyse consumption Wiedmann (2009). He provided an overview of the methodological features of around 20 studies between 2007 and 2009, focussing on consumption-based accounting (CBA) of greenhouse gas (GHG) emissions and resource requirements, and its relevance to policy and decision-making. He highlighted the limitations associated with using MRIO analysis and the issues to be addressed, including sector aggregation, treatment of the Rest of the World (ROW) region, monetary exchange rates, treatment of trade flow matrices and uncertainties with trade statistics. In 2011, Hertwich provided a review of the environmental impacts of consumption, including the emissions and resource requirements of final demand by households and government in different countries (Hertwich). He pointed out that high sector aggregation in MRIO analyses can introduce errors, and discussed the impacts of consumption (with particular reference to input-output modelling) on the amount of emissions and resource use.

To the authors' knowledge, no further studies of the overall development in the use of MRIO analysis for quantifying the impacts associated with consumption of goods and services have since been published. However, the number of publications addressing 'consumption' with 'input-output analysis' has risen sharply. A number of special issues have been published in the the *Journal of Industrial Ecology* highlighting the role of footprint[2] analysis in undertaking consumption-based accounting, and the need to strive for sustainable production and consumption patterns. Of particular relevance to this review are the articles published in the special issues: *Frontiers in Footprinting* (Lifset 2014), *Charting The Future of Life Cycle Sustainability Assessment* (Gloria et al. 2017), *Exploring the circular economy* (Bocken et al. 2017) and the *DESIRE Project* focussing on the use of MRIO tables for assessing resource use and

[1] Citation taken from http://www.adamsmith.org/quotes referring to The Wealth Of Nations, Book IV Chapter VIII, v. ii, p. 660, para. 49; first published in 1776.
[2] The term 'footprint' is used for holistically capturing the impacts of human consumption on the environment, explained further in Section 3.1.

resource efficiency (Tukker et al. 2018). In this paper, we account for developments in the field since 2011. Our literature overview expands on prior work in three aspects:

1) We provide an overview of the evolution of MRIO databases and the addition of greater sectoral and regional detail and discuss what benefits derive from these enhancements;
2) We discuss work that includes a broader range of indicators than those covered in earlier studies and mention studies that have employed these indicators for analysing impacts related to cities;
3) We focus in on social indicators and discuss the limitations and future needs and applications of this new and rapidly growing field.

Section 2 provides a discussion of the evolution of MRIO databases, in particular the greater sectoral and regional detail that is currently being added. Section 3 presents advancements in the field of indicator development, with a special emphasis on social indicators. It focuses on the growth of social indicators and current limitations. Section 4 provides examples of the applications of CBA using MRIO analysis to analyse impacts related to cities. Section 5 provides concluding remarks and avenues for future development of the field of extended global MRIO analysis.

2 Evolution of MRIO databases and virtual laboratories

In this section, we first introduce the various global MRIO databases that have been developed since 2011 and have subsequently been updated, followed by a discussion of virtual laboratories that have the potential to make MRIO databases more accessible for collaborative research and for providing the computing capacity needed to support greater sectoral and regional detail.

2.1 Global MRIO tables

Whilst the basic input-output methodology pertaining to industrial ecology applications has not changed fundamentally, there have been several innovations around increasing global coverage, resolution and accuracy of input-output data. Since the reviews by Wiedmann (2009) and Hertwich (2011), available computing power has grown considerably. This has enabled the development of MRIO databases containing data for hundreds of countries. Wiedmann et al. (2011a) attributed the rapid growth of MRIO databases to the increasing need for global analytical capacity in sustainability research, particularly related to the globalisation of production and consumption practices and the versatility afforded by MRIO databases in understanding policy implications, risk and vulnerabilities of important contemporary issues such as resource exploitation, ecosystem health, social cohesion, inequality, poverty or child labour.

Several global MRIO datasets were summarised in a 2013 special issue of *Economic Systems Research* (Tukker and Dietzenbacher 2013) and elsewhere (Murray and Lenzen 2013). Here, we focus on four, which have been updated over the years: the Global Trade Analysis Project MRIO table (GTAP-MRIOT), the World Input-output Database (WIOD) project, EXIOBASE and Eora.

The Global Trade Analysis Project MRIO table (GTAP-MRIOT) is based on the GTAP database, developed by the Center for Global Trade Analysis at Purdue University. The current version, called GTAP 9 Data Base features 140 countries and 57 sectors, with information on carbon dioxide emissions and five labour skill categories (GTAP 2017). It is a collaboration of researchers and policy makers, who contribute to database development and, along with many others, use the database to answer questions, for example about value added in global production chains or the footprints of products (Andrew and Peters 2013). The World Input-output Database (WIOD) project (Dietzenbacher et al. 2013), updated in November 2016 provides detail on 56 sectors for 28 European Union countries and 15 other major countries for years 2000 – 2014 (compared to years 1995-2011, in the 2013 release). The recent update of WIOD includes detailed data on sectors pertaining to manufacturing and business services, to enable a more comprehensive analysis of global value chains (Timmer et al. 2015). The 2013 version of the data set offers information on socioeconomic and environmental accounts. The socioeconomic accounts are expected to be made available for the 2016 version in early 2018 (WIOD 2018). Recently, WIOD was extended at sub-national level to include all NUTS (Nomenclature of territorial units for statistics) regions of Europe (Thissen et al. Forthcoming 2017). The first version of EXIOBASE was developed under the EXIOPOL project (Tukker et al. 2013). Since then, the database has been updated under the CREEA[3] and DESIRE[4] projects to yield EXIOBASE2 and EXIOBASE3, respectively (Wood et al. 2015; Stadler et al. 2017). The database includes information on 15 land use types, 48 types of raw materials, 172 types of water uses and three employment skill levels for comprehensively quantifying resource footprints of nations (Tukker et al. 2014; Tukker et al. 2016). EXIOBASE3 features data on 44 countries plus five ROW regions, 200 products and 163 industries. A special issue on the DESIRE project provides information about the construction of EXIOBASE3, and the use of this updated database for assessing the environmental impacts embodied in trade (Tukker et al. 2018). Eora was developed at the University of Sydney (Lenzen et al. 2013a). At the time of construction, it covered 187 countries, with a range of 25-400 sectors depending on a country, and 35 environmental indicators over the period 1990-2011. Since then it has been updated to extend the time-series to 2014 and to include up to 220 countries and a range of social accounts (e.g. employment, corruption and poverty). It has been applied to questions on global supply chain GHG emissions (Malik and Lan 2016) as well as biodiversity (Lenzen et al. 2012) and water use (Lenzen et al. 2013b).

These databases vary in the number of regions, sectors and physical account extensions and follow different approaches for the compilation of global MRIO data. Some of the differences include varying data sources used for the construction of the tables and different approaches used for harmonizing data. For example, the construction of the EXIOBASE relied on a multi-stage process of harmonization, whereas the Eora database followed a single automated reconciliation step at the time of construction (Geschke et al. 2014). Understanding what questions each MRIO database was developed to address and why there are differences in results, assists researchers in identifying the best one for the job. To this end, another special issue of *Economic Systems Research* was devoted to analysing the differences between the several databases presented above (Inomata and Owen 2014). Unsurprisingly, differences in the compilation of MRIO tables mean that no two databases yield exactly the same analytical outcomes for consumption-based accounting (Owen 2017). For example Steen-Olsen et al. (2014) analysed the effect of sectoral

[3] CREEA: Compiling and Refining of Economic and Environmental Accounts.
[4] DESIRE: Development of a System of Indicators for a Resource efficient Europe.

aggregation on carbon dioxide multipliers, concluding that those databases with more detailed sectoral resolution showed more accurate results.

2.2 Sub-national MRIO tables

Over the past few years advances have been made in adding sub-national, regional detail to industrial ecology studies, such as for Australia (Daniels et al. 2011; Lenzen et al. 2014), Spain (Escobedo-Cardeñoso and Oosterhaven 2012; Cazcarro et al. 2013), China (Feng et al. 2013; Wang et al. 2015; Zhao et al. 2015; Wiedenhofer et al. 2017) and Germany (Többen and Kronenberg 2011; Többen and Kronenberg 2015). One of the main challenges for constructing sub-national MRIO tables is the absence of detailed data at a sub-national level. In such a case, non-survey methods are often used for constructing sub-national input-output tables, as demonstrated by Többen and Kronenberg (2015), who used the CHARM non-survey method for their study.

Sub-national MRIO tables are useful for understanding the impacts of inter-regional interactions in a country. Understanding these interactions is crucial for a large country such as China. For example, Feng et al. (2013) and Su and Ang (2014) used a sub-national MRIO table of China for quantifying emissions embodied in China's inter-regional trade. Likewise, Feng et al. (2012) used China's sub-national MRIO table for appraising the regional flows of water. (Dietzenbacher et al. 2012) demonstrated that a conventional IO table is unable to distinguish between domestic production and the production of both processed and normal exports. The authors therefore used a tripartite IO table to make a distinction between the three classes of production, concluding that for the case of China assessments using an ordinary IO table result in an overestimation of emissions embodied in China's exports (see also (Su et al. 2013)).

In addition to understanding inter-regional feedbacks, sub-national MRIO tables are also being used for enumerating the environmental, social and economic impacts of a new product or industry in a regional economy. This is evident in a study undertaken by Malik et al. (2015), who analysed the triple bottom line impacts of biofuel production in Western Australia. Likewise, Rodríguez-Alloza et al. (2015) enumerated the energy and greenhouse gas requirements of a new technology for road pavement construction in the Australian state of New South Wales (NSW). Recently, sub-national input-output tables have been constructed for a number of countries such as China (Wang 2017) and Indonesia (Faturay et al. 2017) with the advent of virtual laboratories (Section 2.4). These detailed sub-national tables have also paved way for regional assessments for enumerating the impacts of cities, in particular greenhouse gas emissions (See Section 4).

2.3 Hybrid models

Advances have been made in improving the accuracy of IO models by replacing monetary data (which may be affected by price inhomogeneity) with physical data in hybrid-unit models. Examples are the construction of hybrid tables using the EXIOBASE database (Merciai and Schmidt 2017), calculation of raw material consumption (the material footprint) for the European Union (Schoer et al. 2012), inland marine transportation (Ewing et al. 2011), disaggregation of the electricity sector in a Chinese input-output model to evaluate the primary energy embodied in Chinese final consumption (Lindner and Guan 2014) and the construction of a multiregional solid waste account (Tisserant et al. 2017).

Another advance has been the adaptation of global and sub-national MRIO frameworks to include process-based, life cycle inventory data to enable hybrid life cycle assessment (LCA) applications. Applications have focussed on the assessment of renewable energy technologies based on integrated hybrid LCA by linking process data to IO matrices (Acquaye et al. 2011; Wiedmann et al. 2011b; Acquaye et al. 2012; Hertwich et al. 2015) or by inserting new sectors derived from process information into the IO tables (Malik et al. 2015; Moran et al. 2015; Teh et al. 2017). MRIO-based hybrid LCA represents a significant way forward in IO-assisted LCA, because with increasing globalisation, LCA applications will increasingly deal with functional units that draw on inputs sourced from many countries. Only a MRIO model underpinning a hybrid LCA exercise can ensure that country-specific production recipes as well as international trade are being considered during the enumeration of a functional unit's supply chain. Hybrid IO/LCA will increasingly be recognised as an important tool as civil society, organisations and governments seek to report progress towards the Sustainable Development Goals (SDGs), more so as the UN prepares to update the guidelines on Social Life Cycle Assessment (Ekener 2017).

2.4 Advent of virtual laboratories

Whilst the creation of a number of MRIO databases has undoubtedly advanced the field of IOA; it has inevitably been a time-consuming and tedious process with possible replication of people power and resources. To automate and streamline the process of MRIO table compilation and update, researchers from a consortium of Australian academic institutions took on the task of constructing the Industrial Ecology Virtual Laboratory (IELab) infrastructure for compiling the most-detailed sub-national input-output table, to date, for Australia (Lenzen et al. 2014). Based on a unique root-base-branch relationship, the Australian IELab allows for data to be stored in the most detailed regional and sectoral classification at the root level. Note that the data are so detailed that no computing power currently exists for building a table at the resolution specified in the root classification. Whilst impossible to construct a table at the root classification, the regional and sectoral resolutions can be aggregated to construct tables that are within the processing power of current computing technology, thus giving users the flexibility of defining the regions and sectors to be included in a MRIO table depending on their research question. This flexibility of the IELab has resulted in a range of case studies, for example triple bottom line assessment of biofuel production (Malik et al. 2015; Malik et al. 2016), input-output analysis of waste flows (Reynolds et al. 2014; Fry et al. 2016; Reynolds et al. 2015a), small island assessments (Malik 2016), environmental impacts of food production (Reynolds et al. 2015b), carbon footprinting of cities (Chen et al. 2016b; Wiedmann et al. 2016), renewable electricity generation (Wolfram et al. 2016) and the assessment of construction materials and the built environment (Teh et al. 2015).

In addition to giving users the flexibility to construct customised IO tables (Geschke and Hadjikakou 2017), the IELab provides a range of features for using the IO tables for footprint assessments or for quantifying uncertainty in MRIO data. Wiedmann (2017) provided a review of 30 case studies published by expert users using the IELab platform by surveying the users to determine the potential of the lab in enabling input-output research. The author found that two-thirds of the studies were only made possible because of the IELab, and an additional six would have required substantial input of time and resources. Whilst the current make-up of the IELab has restricted its update by non-expert users (Wiedmann 2017), it is nevertheless a powerful tool for undertaking timely and policy-relevant applications, as demonstrated by Lenzen et al. (2017b). In addition to uses in industrial ecology, sustainability assessment, economic modelling (Wiedmann 2017), Lenzen et al. (2017a) used the IELab for disaster modelling. Within two months of Cyclone Debbie that hit Queensland, Australia in March, 2017, Lenzen et al. (2017a) were able to assess the employment and value-added supply chain effects of the disaster; the analysis was made possible by timely data provision and representation of regional detail in cyclone hit areas.

With the benefits of the lessons learned during construction of the Australian IELab and the provision of advanced tools, large-scale databases and significant RAM in order to carry out Australian applications at a higher sectoral and regional resolution than previously possible, efforts are now underway to extend the IELab platform to a global level. The aim of the global IELab is to bring together some of the aforementioned Global MRIO databases on one platform, to establish the means for regularly updating global MRIO frameworks, fostering collaboration among researchers around the world and to facilitate global cross-disciplinary research (Lenzen et al. 2017c). Based on the Australian prototype, a virtual laboratory harbouring sub-national detail has been developed for China (Wang 2017) and Indonesia (Faturay et al. 2017). Additionally, a number of existing MRIO databases, such as WIOD and EXIOBASE, have been implemented in the Virtual laboratory environment (see (Rahman et al. 2017; Reyes et al. 2017).

As evident from the research presented in this section, we recognise that the virtual laboratory infrastructure is relatively new and its use as yet is mostly based in Australia. However we believe that virtual laboratories have the potential to facilitate timely research of topical issues of political importance (such as disasters). It would therefore be interesting to apply this capability to a wide range of applications undertaken by research groups around the world.

3 Indicator development

Input-output frameworks have increasingly been coupled with non-economic, physical data to improve resolution or introduce additional capability for connecting economic and physical accounts. Ewing et al. (2012), for example, created a detailed account of the mass flow of agricultural, livestock products, fishery and forestry products alongside the monetary use account in a MRIO framework. The benefit of such an account is that additional, product-specific attributes such as water use data can be contained in the mass-unit account while maintaining transparency and integrity in the less detailed monetary dataset. This allows for a much more refined calculation of environmental footprints of consumption of individual products. Such MRIO modelling has been applied in several studies to evaluate different types of consumption footprints for the European Union and individual countries (Steen-Olsen et al. 2012; Weinzettel et al. 2013; Weinzettel et al. 2014). Similarly non-economic social data have been used to extend the capability of economic accounts. The analytical capacity gained is ever more important since the United Nations published their 17 SDGs and 169 targets to be met by year 2030 (UN 2015a). Xiao et al. (2017a) provide an example of the analytical capability provided by a combination of data sets. These researchers coupled a MRIO model with the Social Hotspots Database (Xiao et al. 2017a) to analyse the consumer risk footprint of nations for five SDGs using four social indicators. Attempts are underway to develop a comprehensive set of indicators for assessing the performance of world nations in meeting the SDG goals and targets (FAO 2017a; Sachs et al. 2017)
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3.1 Environmentally-extended MRIO (EE-MRIO) analysis

When considering environmental impacts, Hertwich (2011) found that there had been few applications of IOA to consumption impact studies beyond energy use and GHG emissions. In his analysis of the use of MRIO analysis for CBA, Wiedmann (2009) also found a strong focus on GHG emissions, in particular carbon dioxide (CO_2). Whilst energy and GHG emissions are still common consumption impacts studied using IOA, the field has broadened considerably. Environmental footprinting as a technique has gone through a number of cycles, from providing a single number of integrated environmental impacts to a more detailed accounting of a single type of impact (Hoekstra and Wiedmann 2014; Lifset 2014). In general, an environmental footprint summarises the total pressure exerted on the environment by the use of resources or the generation of wastes or emissions by a consumption activity. Increasingly, there are attempts to express these pressures as actual environmental impacts as defined in LCA, e.g. global warming for GHG emissions (ISO 2013), water scarcity or pollution for water use (ISO 2014) or resource depletion for material extraction (Fang and Heijungs 2014). In any case, footprinting remains a popular application of IOA to evaluate the impacts of consumption. This includes carbon footprints[5], water footprints[6], material footprints[7], biodiversity footprints[8], and various other environmental pressures[9]. Note that the references listed in footnotes 5-9 are not exhaustive but are examples of a range of footprinting studies.

When calculating footprints using MRIO analysis, it is crucial to understand the influence of aggregation or disaggregation of IO sectors or physical accounts data on calculating impacts. This is particularly true for environmentally-extended assessments. A number of authors have analysed the effect of sector aggregation in yielding uncertain results or commonly called 'aggregation bias' for material (de Koning et al. 2015; Piñero et al. 2015; Majeau-Bettez et al. 2016) and carbon flows (Su et al. 2010; Steen-Olsen et al. 2014). Aggregation bias is particularly true for assessments where the IO tables feature an aggregation of all agricultural commodities into one sector called "Agriculture". As Lenzen (2011) pointed out using the following example, this can lead to significant errors: "*if a small rice sector and a large wheat sector are aggregated into 'grains growing', most of the water use may be associated with the smaller rice sector, thus yielding a grossly underestimated water intensity for rice, and a grossly overestimated water intensity for the majority of the grains growing represented by wheat".* Lenzen (2011) concluded that disaggregation of input-output data or environmental data yields more superior results than aggregation of these data.

Whilst carbon and energy footprints have been the focus of many studies thus far, water footprinting has seen a sudden increase in recent years. A number of special issues have been published focussing on water-related research, such as on "Input-output and Water (Duarte and

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[5] *(Berners-Lee et al. 2011; Davis et al. 2011; Larsen and Hertwich 2011; Larsen et al. 2012; Ala-Mantila et al. 2013; Bastianoni et al. 2014; Caro et al. 2014; Zhang et al. 2014; Anderson et al. 2015; Caro et al. 2015; Kagawa et al. 2015; Zhang et al. 2016; Brizga et al. 2017; Caro et al. 2017; Li et al. 2017; Moran et al. 2017; Wood et al. 2017)*

[6] *(Feng et al. 2011; Xiao et al. 2011; Zhang et al. 2011a; Zhang et al. 2011b; Feng et al. 2012; Lin et al. 2012; Dong et al. 2013; Shao and Chen 2013; Cohen and Ramaswami 2014; Huang et al. 2014; Wang et al. 2014; Han et al. 2015; Zhuo et al. 2016; Liu et al. 2017; Ali et al. 2018)*

[7] *(Bruckner et al. 2012; Schoer et al. 2012; Wiebe et al. 2012; Giljum et al. 2015; Wiedmann et al. 2015a, Wiedmann 2015b; Giljum et al. 2016; Lutter et al. 2016; López et al. 2017)*

[8] *(Lenzen et al. 2012; Moran et al. 2016; Kitzes et al. 2017; Moran and Kanemoto 2017; Wilting et al. 2017; Wilting and van Oorschot 2017)*

[9] *(Zhou and Imura 2011; Duarte and Yang 2011; Ewing et al. 2012; Galli et al. 2012; Moran et al. 2013; Chen and Chen 2015; Li et al. 2015; Nansai et al. 2015; Shigetomi et al. 2017; Owen et al. 2018)*

Yang 2011)", "Water Footprints and Sustainable Water Allocation (Hoekstra et al. 2015)" and "Water Footprint Assessment (Hoekstra et al. 2017)". The forthcoming special issue "Water Footprint in Supply Chain Management" is currently open for submissions (Sustainability 2017). An article by Daniels et al. (2011) in the special issue of *Economic Systems Research* provided a review of MRIO approaches and water footprints for regional sustainability analysis and water policy. Similar to the developments in carbon footprint accounting there is an ongoing debate about the respective strengths and weaknesses of bottom-up and top-down approaches to water footprinting. Daniels et al. (2011) argue that Environmentally-Extended MRIO (EE-MRIO) is well suited to complement process-based approaches to water footprinting by expanding the supply-chain coverage and by establishing the geography of embodied water. Another innovation in water footprinting is the inclusion of scarcity. In calculating physical flow, it is not appropriate simply to add together supply-chain contributions of water from Ireland and water from Uzbekistan, the latter being much scarcer (Lenzen et al. 2013b) – also see (Sachs et al. 2017) for discussion of this issue in relation to SDG 6 that aims to achieve universal access to clean water and sanitation for all by year 2030. Similar assessments were undertaken for the European Union (Serrano et al. 2016). Recent focus of research into Water footprinting is to measure progress towards SDG 6 (Hoekstra et al. 2017).

In addition to calculating a range of footprints separately (see footnotes 5-8), scholars now acknowledge the overlapping nature of footprint indicators (Simas et al. 2017). The first comprehensive and consistent inclusion of carbon, water and ecological footprint indicators in an EE-MRIO framework was described by Galli et al. (2012). The authors argue that combining these overlapping, interacting and complementing indicators in a 'Footprint Family' and one modelling framework is of benefit for decision-making. They test this integrated framework against some of the main European and international policy objectives and outcomes. More specifically, footprint indicators have been combined with an EE-MRIO model (Weinzettel et al. 2011) in the project One Planet Economy Network Europe (OPEN:EU) funded by the European Commission. A user-friendly analysis and scenario tool was developed from the model. The EUREAPA tool[10] allows the user to quantitatively unravel global supply chains using a carbon, ecological and water footprint indicator (Roelich et al. 2014). The links between the consumption of a product type in one country and its production impacts elsewhere are identified and the top ten sources of greatest impact are displayed. The scenario editor within the tool can be used to explore the environmental pressures associated with changes in population, consumption patterns, production technology or trade over time. Such functionality had not been provided in an EE-MRIO online tool before and the new information is presented in a useful and accessible way. It is worth mentioning that researchers have explored the distinction between pressure and impact type indicators. Traditional footprints report on environmental pressures, Verones et al. (2017) follow the DPSIR (drivers, pressure, state, impact and response) framework to link pressures to consequences of consumption. The authors highlight the need for assessing impact footprints for effective policy making.

3.2 Social footprints and socially-extended IOA

One of the applications of IOA that was not well considered prior to 2010 is the use of socially-extended input-output matrices to study social ecology and social impacts. Although post World

[10] *https://eureapa.net*

War II there had been a focus on using IO to assess social progress, the field did not significantly expand for the next few decades at the expense of the development of environmentally-extended input-output analysis (McBain and Alsamawi 2014). A recent special issue on Social Life Cycle Assessment (Gloria et al. 2017) clearly demonstrates advancements in this growing field. The UNEP/SETAC guidelines on social LCA, currently being updated (Ekener 2017) and the accompanying methodological sheets (Benoit-Norris et al. 2011) have contributed to the understanding of consumption through the use of IOA assisted LCA. The use of socially extended MRIO is particularly useful for considering the human impacts of consumption from global supply chains. Examples include consideration of the human toll of supplying tantalum to the global marketplace from a conflict zone (Moran et al. 2015) and the impact of commodities produced for US domestic consumption on inequalities in the world system (Prell et al. 2014). MRIO analysis is now being used for enumerating social footprints, for example employment (Alsamawi et al. 2014a), labor (Simas et al. 2014; Simas et al. 2015), inequality (Alsamawi et al. 2014b), and other social indicators (Hardadi and Pizzol 2017).

One of the abiding challenges to conceptualisation of social footprint work is that of causality. Environmental footprints establish a causal link between trade and say, emissions or water use. We could say for example that: 'production of this good caused these emissions'. In the case of social footprints there is no such clear-cut relationship between product, consumer and social indicator. For example we cannot say that production of this good caused this amount of corruption (or inequality or ill-health etc.). Social footprint researchers have addressed this issue by saying that consumers who knowingly purchase goods that embody high levels of for example, hazardous employment, are implicated in the continuation of such employment. By purchasing 'contaminated goods' the consumer could be said to tacitly endorse dangerous employment conditions. Purchase of such goods can be characterised as a missed opportunity to pressure governments and global brands to improve working conditions (Xiao et al. 2017a). At the same time researchers have been at pains to emphasise that simply not purchasing a 'contaminated' good is no solution to improving worker conditions; any temporary suspension of purchase needs to be accompanied by pressure on suppliers for improvements.

Another issue is that of data additivity. Data in an IO framework must be able to be added. However, much available social data cannot fulfil this basic requirement. For example data might be provided in percentages such as 'percentage of workers affected by x ' (e.g. corruption) or by means of say, a five point scale of social risk (Benoit-Norris et al. 2017). To accommodate such cases in an IO framework requires trade-offs. In the case of a five-point scale, such as that used by the Social Hotspots Database (2017), risk levels can be allocated a weighting to allow additivity. In the case of corruption, national indices can be converted into an additive quantity such as corruption-affected jobs per sector, by applying a country's percentage corruption value to the number of workers in each sector of the economy. The county's overall corruption risk is applied to each sector and since the number of workers in each sector is known the percentage of workers affected by corruption can be translated into a number of workers. One obvious outcome of this method is that more workers means more corruption (Geschke 2017) which may or may not be the case.

These are imperfect measures, however if such calculations prove useful, for example in tracking progress towards the SDGs, there will be incentive to improve or adjust data collection methods and format. Meanwhile researchers continue to provide detailed description of their methods and document their assumptions. Given how useful satellite accounts are for analysing consumption activities in supply chains using MRIO analysis, a consistent approach to the generation of data is required. To this end, the UN System of Environmental-Economic Accounting – Central Framework (UN 2014) provides a framework for the development of environmental satellite accounts in a consistent manner, and there have been calls for the development of a similar system with respect to social accounts (McBain and Alsamawi 2014).

A third challenge to social IO analysis is how IO frameworks cope with big differences in regional and sectoral detail. Some data, for example that provided by the International Labour Organization (ILOSTAT 2017) are highly aggregated while others, for example, survey data dealing with local issues in a factory or town, are highly detailed and specific. In the latter case if the only IO model available is at the national level then all detail will be lost, rendering any calculation futile. Solving the problem of marrying big and small data without loss of information was one of the tasks identified as important by the Australian IELab team. The work described in Geschke (2017) represents a technical breakthrough in this field. However, applications are thin on the ground and much work needs to be done to operationalize the potential. The challenge should progressively be addressed as the IELab platform expands to become a global IELab, and researchers from around the world begin to make use of this capability to address specific issues or track progress towards the SDGs.

4 Example application of global consumption-based accounting - cities

There have been several applications in specific research areas related to consumption. Here we briefly present some of the literature on the consumption impacts of cities.

Input-output analysis is increasingly being applied to calculate the environmental footprint from urban consumption. Wright et al. (2011) and Baynes and Wiedmann (2012) summarised the literature on consumption-based accounting at the city scale up to 2011/12. Since then IO-based carbon footprints and related environmental indicators have been estimated for example for: Aveiro, Portugal (Dias et al. 2014); Helsinki, Finland (Ala-Mantila et al. 2013); four Chinese Megacities (Feng et al. 2014); Glasgow (Hermannsson and McIntyre 2014); 434 municipalities in the UK (Minx et al. 2013); Beijing (Liu and Zhang 2012; Wang et al. 2013); the Beijing-Tianjin agglomeration and other regions in China (Yao et al. 2013), amongst others. Such studies provide new insights into the relationship between urban consumption and lifestyles and tele-connected environmental impacts elsewhere.

Increasingly, sub-national MRIO tables (Yao et al. 2013; Feng et al. 2014) and even city-level IO tables (Wang et al. 2013) are used for calculating impacts of cities. A typical finding for large cities was presented by Feng et al. (2014), who calculated that more than 70% of CO_2 emissions related to the consumption of goods in Beijing, Shanghai and Tianjin occur outside of the city boundary. More recently, Wiedmann et al. (2016) introduced the concept of a 'city carbon map', exploiting the spatial detail of sub-national MRIO data in the IELab for a case study of Melbourne, Australia. The authors claim that carbon maps show "*local, regional, national, and global origins and destinations of flows of embodied emissions*", thus allowing the enumeration of both the direct and indirect emissions from a city. The carbon map concept has since been applied to other Australian and Chinese cities and the embodied carbon networks between them (Chen et al. 2016b; Chen et al. 2016a; Chen et al. 2017).

5 Conclusions and future directions

We present an overview of research advancements in the development of multi-regional input-output (MRIO) databases and the development of a range of environmental, economic and in particular social indicators for undertaking sustainability impact assessments. Advancements in MRIO analysis, especially the construction of detailed databases and improvements in computational power, have provided researchers with architecture for undertaking consumption-based assessments. We demonstrate the evolution of MRIO databases and virtual laboratories as vital tools for understanding industrial ecology and in particular for analysing global supply chains and international trade. Using information resulting from MRIO tables, consumers and producers can develop a better understanding of the impacts, with a view towards modelling improved sustainable outcomes for the future. In addition to traditional assessments on carbon and energy based accounting, we present an overview of the surge in applications in water footprint assessments. One of the applications that had not been well considered prior to 2010 is the extension of MRIO matrices with social indicators to analyse supply-chain effects for employment, inequality, poverty, occupational health and safety, labor and gender equity. The MRIO tables can also be coupled with data from databases, such as the Social Hotspots Database, which harbour information on detailed social indicators. However, due to a lack of detailed social data for sectors and regions, coupling of such data with a MRIO table comes with its challenges. For the case of corruption, Xiao et al. (2017b) applied an assumption that the higher the number of people employed by a sector, the higher the corruption in that sector. In the absence of detailed data, this might be satisfactory as a first cut exercise, however for informing policy-making, further deliberation of data for informing such an analysis is crucial.

Future of MRIO development: We have made considerable progress since the conception of input-output analysis by Wassily Leontief, however there is still considerable capacity for enhancing its capability as a tool for informing policy-making at a local, national and global level. In the area of MRIO development, the future could include construction of nested input-output tables. Whilst this has been done for China (Wang et al. 2015), a country with a vast geographical area and complexity, nested tables for other countries of the world would pave the way for assessing the linkages between cities in two different countries. The use of such tables is particularly important for undertaking consumption-based accounting of cities that import a majority of their goods from outside their boundary. Chen et al. (2017) carried out consumption based accounting of two large cities of Australia – Melbourne and Sydney, and found that the source of a large chunk of imported emissions for these cities lies outside of Australia – 55% for Melbourne and 71% for Sydney. In an additional study, by linking sub-national MRIO tables of China and Australia Chen et al. (2016b) were able to identify trade links between different Australian and Chinese cities. The roadmap from national IO tables to global MRIO tables to nested MRIO tables does not come without challenges. At the time of construction of nested MRIO tables linking the sub-national MRIO table of China with the global MRIO table, Wang et al. (2015) were faced with computational challenges, requiring the authors to adopt a two-step procedure, focussing first on the construction of a MRIO table of China and integrating that into the global table in a second step. It is worth mentioning that whilst we have made significant advancements in computational power for constructing and processing MRIO datasets, the construction of a large inter-regional inter-country data-set harbouring sub-national data for every country of the world is far from being realised.

Future of indicator development: The future for the development of new, unique and harmonised indicators for inclusion into a MRIO database would very much need to be informed by United Nations goals and targets on sustainable development. The UN SDGs are a prime example of where MRIO data-sets could be used for assessing a country's progress, at the same time benchmarking the performance in comparison with other world nations. Xiao et al. (2017a) demonstrate that MRIO analysis can be used for informing progress towards SDGs, however there is pressing need to develop indicators that can inform all 17 goals set by the UN and the accompanying 169 targets. As an example, Goal 2 aims to end hunger by 2030 (UN 2015a). At the time of writing, there was no published research investigating the contribution of international trade in causing hunger. The contribution of international trade in promoting or eradicating hunger is unclear. It has been suggested that international trade opens avenues for developing countries to have access to large global markets allowing them to specialise in production and exploit economies of scale. There is, however, another school of thought that challenges this argument on the basis of unfair trading rules that are biased towards developing countries (FAO 2017b; OXFAM 2017). A potential integration of a data-set such as the Global Hunger Index (IFPRI 2017) with a global trade database, coupled with additional data for harmonising the GHI dataset with the trade model, could yield useful insights into the implications of international trade on hunger in developing and under-developed nations. It is important to note that whilst for environmental indicators such as carbon emissions and energy use, we can enumerate the amount of emissions embodied in the consumption of a particular good or service, such a link is not clear-cut for social issues such as a hunger. These intrinsically complex issues require exploration of potential indicators that could be coupled with the global database for undertaking a supply-chain assessment. The future of indicator development very much relies on coupling big data with small data at a local and regional level. The report on the success of the Millennium Development Goals calls for "*…a data revolution to improve the availability, quality, timeliness and disaggregation of data"* to track progress towards SDGs (UN 2015b). Integration of big and small data is crucial for understanding and quantifying the environmental issues faced by world nations, particularly low (-middle)-income countries, who often lack the resources and expertise in this area. This is definitely an area of research that is open for development: production of comprehensive, detailed and complete small data for integration into big data-sets for informing policy-making. The World Bank is leading the way in initiatives for collecting data for low (-middle)-income countries, as indicated by Kaushik Basu, Chief Economist of the World Bank**:** *"Data gives representation to people who may otherwise be marginalized and forgotten, hence our decision to greatly step up efforts to collect more and better quality data in developing countries* (The World Bank 2015)*".* The input-output research community has a crucial role to play in informing such efforts and for developing metrics and methods for integrating small data with big data.

Conflict of interest

The authors declare no conflict of interest.

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