Towards a Material-based Indicator of Bioeconomic Transition

Raphael Asada, Tobias Stern

University of Graz, Institute of Systems Sciences, Innovation and Sustainability Research, Merangasse 18/1, 8010 Graz, Austria

The terms bioeconomy and bio-based economy refer to one of the recently most prominent political-economic concepts in Europe addressing ecological objectives. Measuring bioeconomic progresses is vital for future socioeconomic and political decisions. Previous studies on the state of bioeconomy were based on an initial decision, what bioeconomy is, i.e. which sectors of an economy are considered as bioeconomic. However, this contradicts the fact, that sectoral prioritization within bioeconomy strategies around the world differ considerably. In order to overcome the problem of a lacking definition of bioeconomy we suggest to monitor the potential outcome of a bioeconomic transition instead, which is first and foremost a reduction in fossil resources dependency. As a first step towards a material-based indicator, extraction of fossil resources and biomass embodied in the consumption patterns of a broad set of countries is calculated, employing the World Input-Output Database (WIOD). Additionally, the same indicators derived from a different data source (EORA Footprint Summary) are compiled and compared to the WIOD results. Our results show a correlation between the databases of 0.95 for fossil and 0.99 for biomass raw material consumption. Relative disagreement tends to be lower for larger economies (USA, China, Brazil and India). However, for smaller countries and some outliers (Japan, Australia, Russia and Korea), divergences may be substantial. Based on these findings we draw conclusions on the possibility to test, to which extent these inconsistencies influence regression-based explanations of raw material consumption, in order to disclose their implications for a material-based indicator of bioeconomic transition.

Keywords *bioeconomy, socio-technical transition, raw material consumption, ecological economics, economic geography, input-output modelling*

1 Introduction

The terms “bioeconomy” and “bio-based economy” are currently referring to one of the most prominent political-economic concepts in Europe focusing on ecological aspects i.e. climate change mitigation and reducing environmental impacts (European Commission, 2012). Furthermore, a bio-based economy is intended to have socioeconomic benefits such as fostering economies’ competitiveness, meeting rising demand and counteract resource depletion (ibid.). Measuring and monitoring the state of bioeconomic developments is important for future social, political and economic decisions. Within a DPSIR framework for the bioeconomy, O’Brien et al. (2015) identified production and consumption patterns as the drivers of environmental impacts such as climate change, soil quality depletion and biodiversity loss. In order to investigate these patterns, the authors presented three indicator types, categorized into 1) economic basic data, 2) monitoring of resource use and 3) economic modelling. The first indicator category contains data on turnover, contribution to gross domestic product, employment, potential for innovation, production and consumption, added value and trade balance of bioeconomy. An example for the use of this indicator class can be found in Ronzon et al. (2017). The second class consists of data on global material footprints including water resources as well as on environmental and social consequences of resource related to bioeconomy (e.g. Budzinski et al., 2017). The third class encompasses indicators derived from economic modelling such as CGE and PE models, aiming at estimations on sustainability of bioeconomy, inter alia. All three indicators classes rely on a decision, what bioeconomy is, i.e. which sectors of an economy are considered as bioeconomic.

However, Priefer et al. (2017) found, that corresponding prioritization within bioeconomy strategies around the world differ. Some countries rather focus on traditional biomass producing and transforming sectors (e.g. forestry sector, pulp and paper industry) while others concentrate on high-tech industry (e.g. chemical and pharmaceutical industry). Such divergences have been identified by earlier studies as well (Pülzl et al., 2014; Beermann et al., 2015; FAO, 2016). Additionally, taking the recent literature on bioeconomy into account, Priefer et al. pointed out an ongoing controversy over possible pathways of bioeconomic transitions and shed light on different areas of criticism (strongly technology-oriented focus or inadequate stakeholder integration). Hence, a comprehensive and at the same time precise definition of bioeconomy does not exist at present. On the contrary, the authors recognized a broad consensus across bioeconomy strategies with regard to possible *outcomes* of a bioeconomic transition, which is, first and foremost, a reduction in fossil resources dependency facilitated by an increased use of biogenic resources. Besides, the authors identified further outcomes such as global warming mitigation or creation of jobs in rural areas, which we interpret as secondary effects resulting from the stated shift in raw material use.

From this perspective, the question of bioeconomic transition is fundamentally centered around the interacting uses of fossil resources on one hand and biomass on the other hand within socio-technical systems. Bioeconomy-related literature often takes a production-based perspective and deals with the technical and economic challenges of innovative bio-based applications (for an overview see Priefer et al., 2017) or with the environmental implications of such innovations on the level of the individual product along its lifecycle (see e.g. Krzyżaniak et al., 2018). At the same time, it is obvious that improvements in production efficiency alone are not sufficient to substantially reduce environmental impacts, e.g. to achieve CO_2 emission reduction targets. According to Pothen (2017), increased production efficiency reduced global consumption of raw materials by 7% between 1995 and 2008, while in the same period rising demand overcompensated the savings by a factor of seven. Thus considering the realm of consumption an integral part of bioeconomy and of economy in general, we adopt a demand-driven view and seek to investigate patterns of direct and indirect consumption of fossil resources and biomass across countries as a first step towards a material-based indicator of bioeconomic transition. Due to its outcome-orientation, the indicator's comparability across countries would not be negatively affected by the diversity of bioeconomy definitions in national bioeconomy strategies.

As socio-technical transitions are linked to a variety of technological, organizational, political and economic dimensions (Markard et al., 2012), a useful indicator of bioeconomic transition takes varying country-specific conditions into account and reflects alterations of raw material consumption patterns across space and time in the light of related changes. Economic growth, affluence or final demand, for example, are broadly discussed as key determinants of material use (e.g. Bithas and Kalimeris, 2017, Eisenmenger et al., 2016, Hatfield-Dodds et al., 2017, Krausmann et al., 2009, Pothen, 2017, Schaffartzik et al., 2015, Schandl and Turner, 2009, Shao et al., 2017, Wood et al., 2009). In this context, fossil resource use was found to have a stronger GDP elasticity than biomass (Steinberger et al., 2010, Wiedmann et al., 2015), suggesting, that GDP levels influence the composition of raw material consumption. Wiedmann et al. (2015) introduced further variables and demonstrated that GDP per capita, domestic extraction per capita and population density together explain 46-65% of per-capita biomass consumption variation across countries (77% for fossil resources consumption) in 2008. Besides, consumption of energy from other than combustion and metabolic processes, geographical zone/latitude and land cover may play a role, but also urbanization, inequality, political and demographic structures, regulatory and cultural norms (see Markard et al., 2012), which will be the subject of further work.

In the present conference paper though, we limit our focus to the fundament of a material-based indicator, which is the data describing the direct and indirect raw material consumption (RMC) of fossil and biomass resources by countries. As a consequence of globally interdependent trade flows, calculation of RMC is not trivial. Eisenmenger et al. (2016) showed for Austria, that RMC results may differ greatly depending on approaches and data sources used. The phenomenon of diverging indicators originating from different data sources is also known in the context of climate research (see e.g. Moran and Wood, 2014; Owen et al., 2014; Wieland et al., 2018). Hence, the aim of this study – using methods from the fields of ecological economics and economic geography – is to

- calculate and compare fossil and biomass RMC results derived from two different and independently constructed data sources (WIOD and EORA);
  - include a broad set of countries to reveal possible patterns of agreement and disagreement across countries;
  - cover a time period instead of a single year to compare temporal dynamics of time series resulting from both data sources;
- conclude on inconsistencies between WIOD and EORA results and on the possibility to test, to what extent these inconsistencies influence regression-based explanations of RMC, in order to disclose their implications for a material-based indicator of bioeconomic transition.

2 Methods

Multi-regional input-output analysis is a useful tool for allocating uneven distributed environmental and socioeconomic impacts to final consumption of regions (Wiedmann et al., 2011). Recently, environmentally extended multi-regional input-output analyses (EEMRIO) for consumption-based allocation of raw materials extraction have been conducted (e.g. Bruckner et al., 2012; Schoer et al., 2013; Giljum et al., 2015; Wiedmann et al., 2015; Eisenmenger et al., 2016; Budzinski et al., 2017; Pothen, 2017). The approach facilitates the quantification of raw materials directly and indirectly embodied in final consumption of a country. In literature, the corresponding indicator is called raw material consumption (RMC; e.g. Eisenmenger et al., 2016) or material footprint (MF; e.g. Wiedmann et al., 2015). Input-output modelling is based on information on monetary flows between the sectors of an economy (domestic interindustry exchanges) and from domestic final consumption to domestic industry (Miller and Blair, 2009). Exports and imports are considered by including flows from and to a rest of the world (ROW) aggregate. Multi-regionality is introduced by disaggregating ROW, allowing to trace monetary flows not only within the domestic economy, but within and across all regions included. Environmentally extending these input-output relations by a biophysical quantity layer (e.g. global raw material extraction or CO_2 emissions), the individual contribution of each region's final consumption to the impact investigated is assessed. While EEMRIO for calculating RMC and related indicators is the most advanced approach in terms of depicting global monetary interindustry flows, also single-region input-output variants are possible (Schaffartzik et al., 2014). These applications often rely on additional data from life cycle inventories in order to compensate for the black box nature of ROW.

In order to calculate RMC, we use an EEMRIO model together with domestic material extraction quantities in mass units (DE) as environmental extension, which result from economy-wide material flow accounting (EW-MFA). EW-MFA describes the interaction of economies with their natural environment and the rest of the world via a quantification of domestic raw material extraction, material trade flows as well as domestic waste and emission outputs. For the purpose of this study, only data on domestic raw material extraction (DE) is used, omitting other dimensions of EW-MFA. On its top level, the framework consists of the four main material categories biomass, metal ores, non-metallic minerals and fossil energy carriers. Usually, EW-MFA applications make use of secondary data obtained from national and international providers of data, combined with estimates for material sub-categories not covered (e.g. grazing biomass). In 2007, Eurostat released a compilation guide for economy-wide material flow accounting (EW-MFA), which has been revised several times to the version of 2013 (Eurostat, 2013).

Formally, RMC is calculated according the standard EEMRIO model, as for example described by Moran and Wood (2014), Pothen (2017), Schaffartzik et al. (2014) and Schoer et al. (2012). In this model[1], $\mathbf{Z}$ is a square matrix representing intersectoral monetary flows within and across economies, while monetary flows from final consumption to the sectors are represented by $\mathbf{Y}$. The sectorwise gross output is denoted by vector $\mathbf{x} = \mathbf{Zj} + \mathbf{Yj}$, where $\mathbf{j}$ is a column vector of ones. Derived from $\mathbf{Z}$, the input coefficient matrix $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$ describes the sectorwise inputs necessary to produce one unit of output of that sector in monetary terms. The environmental extension data is stored in $\mathbf{E}$, which quantifies the amount of raw materials extracted from the domestic environment (DE) by each primary sector in mass units. The amount of materials extracted and normalized by gross output is represented by $\mathbf{F} = \mathbf{E}\hat{\mathbf{x}}^{-1}$. Given these variables, raw material extraction embodied in consumption can be calculated by applying the EEMRIO standard model, $\mathbf{M} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}$, where $\mathbf{I}$ is an identity matrix. After calculations according to this model, we aggregated the different final consumption classes (e.g. consumption expenditure by households or governments) country-by-country as well as the sub-types of raw materials (e.g. biomass feed and biomass food).

[1] Matrices are referred to by upper case bold letters, vectors by lower case bold letters. $\mathbf{I}$ denotes an identity matrix, $\mathbf{j}$ a vector of ones. The "hat" operator produces a diagonal matrix from a vector.

3 Data sources

3.1 World Input-Output Database

The World Input-Output Database (WIOD) (Dietzenbacher et al., 2013; Timmer et al., 2015) offers multi-regional input-output tables (IOTs) covering the period between 1995 and 2009 in its 2013 release. The database includes the EU-27 member countries and 13 other major economies, together accounting for 85% of the world GDP. Additionally, a rest of world (ROW) country group is incorporated. Economies are disaggregated to a 35 sectors level in the industry-by-industry format. All flows are expressed in current basic prices. The construction of the IOTs has been based on national Supply and Use Tables (SUTs), on data on international trade, e.g. from the United Nations (UN) Comtrade or from the International Monetary Fund (IMF) trade statistics as well as on OECD and UN National Accounts data (Timmer et al., 2015). Since WIOD was intended to provide time series data, estimates had to be made for countries and years in which no SUTs were available. For this purpose, data from national accounts statistics on outputs, value added, imports, exports and final consumption have been used as constraints, while the intersectoral flows were estimated using an iterative balancing technique (SUT-RAS). Furthermore, harmonization of different levels of detail between the national SUTs including aggregation and in some cases disaggregation of data was conducted. Some proportionality assumptions concerning allocation of import flows to different use categories were introduced. In the step of transforming SUTs into IOTs the so-called fixed product sales structure assumption was applied (Dietzenbacher et al., 2013).

Data for material extension was taken from the Global Material Flow database compiled and maintained by SERI, the Wuppertal Institute, the Institute for Energy and Environmental Research, and the Vienna University of Economics and Business (Genty et al., 2012). The database complies with the nomenclature and accounting principles outlined in Eurostat (2013). It contains data on used an unused extraction of biomass, fossil resources, industrial and construction minerals, and ores in mass units sourced from the Food and Agriculture Organization of the United Nations (FAO), the International Energy Agency (IEA), the United States Geological Survey (USGS) and other organizations. Unused extraction refers to extraction not further processed, e.g. harvest residuals or overburden for mining activities (Lutter et al., 2016). In accordance with literature on raw material consumption (Eisenmenger et al., 2016, Wiedmann et al., 2015), only domestic extraction used is considered in the current work. As bioeconomy is interconnected only with the use of biomass and fossil resources, the results section excludes other material categories. The biomass category covers agriculturally harvested biomass, e.g. crop production and by-products, grazing, forestry, hunting and other biomass (e.g. fibers), transformed to a standardized water content of 15%. Fossil resources include anthracite, coking coal, other bituminous coal, sub-bituminous coal, lignite, crude oil, natural gas, natural gas liquids, peat for energy use, oil shale and oil sands, and other hydrocarbons. For more detailed information see Lutter et al. (2016).

3.2 EORA Input-Output Database

The following section briefly discusses the EORA database and its material extension. This should not hide the fact that the calculation of the EORA-based RMC dataset used for comparison purposes in this study is not our own work. Instead, we use a footprint summary dataset provided on the EORA website.

The EORA database (Lenzen et al., 2012; Lenzen et al., 2013) delivers input-output data for the period 1990–2015 and 187 countries, which is close to global coverage. In its full version, aggregation levels of sectors (or products) differ across countries and range from 25 up to approximately 500. Principal data sources were the national statistical offices, Eurostat, the Institute of Developing Economies Japan External Trade Organization (IDE-JETRO), the OECD, the UN National Accounts as well as UN Comtrade and UN Servicetrade. While different valuation layers are provided in EORA (e.g. trade and transport margins or taxes), physical extension data is limited to be used with the basic price layer. Hence, for environmentally extended applications, WIOD and EORA share the same price concept as a measure of monetary flows. Compared to the construction of the WIOD however, the methodology used for building EORA differed fundamentally. In contrast to WIOD, the EORA initiative made direct use of IOTs from national statistical offices. Lenzen et al. assumed superiority of knowledge of local statisticians and thus avoided data transformation whenever possible. As a consequence of the direct use of national IOTs, no conversion from SUTs was required in these cases, indicating that sales and technology structure assumptions – implicitly embedded in the national IOTs – have been adopted unchanged. Multi-regional IOTs were created in a multi-stage process based on national IOTs and national SUTs. Firstly, an initial estimate of the year 2000 multi-regional IOT was generated and reconciled with the constraints of this year. Initial estimates for subsequent years were derived by scaling prior solutions with inter-year ratios of GDP, exports, imports and value added. Secondly, based on these estimates and constraints data, multi-regional IOTs were obtained by large-scale optimization and iterative balancing techniques (e.g. KRAS).

Material extension data was taken from the Global Material Flow Database published by the Commonwealth Scientific and Industrial Research Organisation, Australia (CSIRO) and linked to the input-output data (see SI Text in Wiedmann et al., 2015)[2]. Schandl and West (2010) outlined the foundations of the database in a study focusing on the Asia-Pacific region. Principally, data compilation was conducted in accordance with a predecessing version (Eurostat, 2007) of the accounting methods sketched in Eurostat (2013). Due to a distinction between industrial and construction minerals, the authors used five instead of the usual four material categories. Key data sources were the FAO, UN Production Statistics, UN Comtrade, and the IEA. Biomass flows represented by the database cover harvest of primary crops, crop residues, grazed biomass, and wood in mass units. While the majority of data was sourced from FAO, crop residues were calculated based on harvest factors and recovery rates from the literature. Grazing was estimated via theoretical feed energy requirements minus energy stemming from use of fodder crops. Again, conversion factors were applied to standardize water contents to 15%. To calculate tonnages of coniferous and non-coniferous wood, densities provided in Eurostat (2007) were adopted. Data for fossil energy carriers were acquired from the IEA, with only minor transformations. Due to limited relevance of the other material categories for the present study, they are not described here; for further information see Schandl and West (2010). The publication does not provide information about compilation of unused material flows.

[2] The footprint summary dataset provided on the EORA website does not include references to technical documentation. We assume that detail information on methodology and data given in the SI Text in Wiedmann et al. (2015) also holds true for this dataset, particularly as they refer to the EORA website for additional results on raw material consumption.

4 Results and Discussion

Figure 1 represents the correlation between annual fossil and biomass RMC results derived from WIOD and EORA across countries and years. Since the two databases are employed to measure the same indicators in the present application, they ideally should show identical results for each year and country. Nevertheless, due to differences in the construction process of the databases, disagreement may occur. Despite of a coefficient of determination of 0.95 or higher, disagreement between databases are pronounced in some cases. The largest relative distances to the inter-model mean (mean between WIOD and EORA regarding a given country and year) are 0.7 for fossil RMC results and 0.5 for biomass. Generally, results for biomass RMC display better convergence. Unsurprisingly and therefore not represented graphically, (temporal) within variance is clearly smaller than between variance across countries.

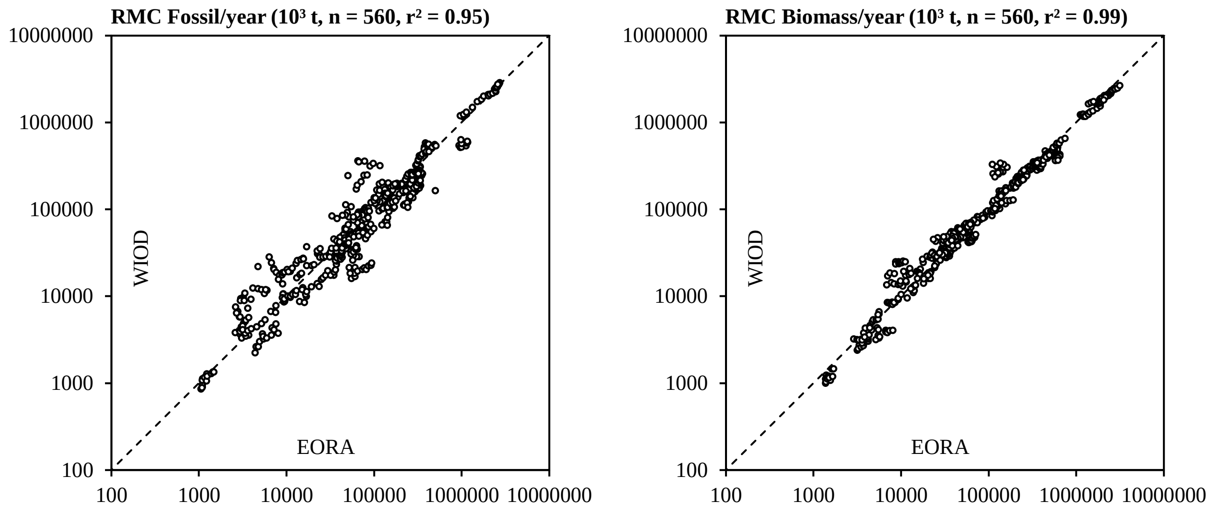

Figure 1: Annual fossil and biomass raw material consumption (RMC) according WIOD (y-axis) and EORA (x-axis) in thousands of metric tons. Data refer to the period between 1995 and 2008 and cover the 40 WIOD countries except the Rest of World (ROW) region with a total of 560 observations.

[Continued on page 8]

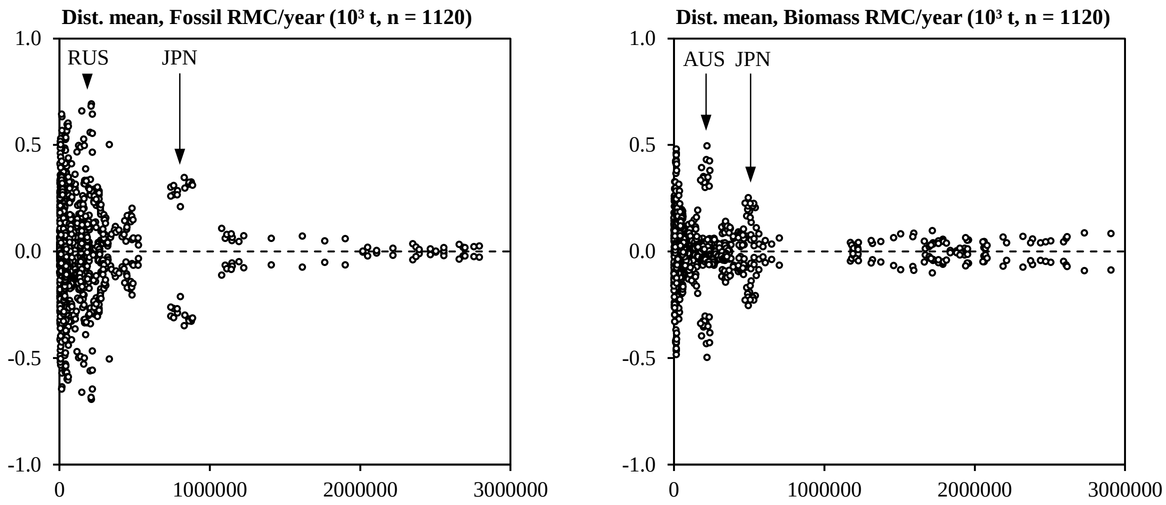

Figure 2: Relative distance from annual inter-model mean (WIOD, EORA) (y-axis) by annual inter-model mean (x-axis) in terms of fossil (left-hand) and biomass (right-hand) raw material consumption (RMC) in thousands of metric tons. Data refer to the period between 1995 and 2008 and cover the 40 WIOD countries except the Rest of World (ROW) region with a total of 1120 observations.

If the relative distances between the annual inter-model mean and the corresponding values in WIOD/EORA are plotted against the inter-model mean, a funnel-shaped pattern emerges (Figure 2). The bulk of data points displaying high disagreement is clustered around an inter-model mean near zero, while the distances tend to decrease with an increasing inter-model mean. Approximately, the larger a country in terms of RMC is, the less disagreement exists between the model's RMC results, for both, fossil and biomass RMC. Thus, distances in absolute terms are not proportionally related to country size. Relative disagreement is particularly low for countries with an annual RMC above 10^9 t (which is the case for biomass RMC of USA, China, Brazil and India; fossil RMC of USA and China).

An interesting outlier is Japan's fossil RMC (cluster of single-year data points marked in Figure 2), which is outside the funnel shape. Across the entire period investigated, the corresponding EORA values are 1.5 to 2 times the values derived from WIOD. Interestingly, there are also above-average discrepancies for Japan's biomass RMC, although less noticeable (EORA values 1.2 to 1.7 times the WIOD values). Nonetheless, the unusual inconsistencies within both material types seem to indicate a common cause. As a second outlier, we identified the biomass RMC results for Australia, where EORA values are 0.3 to 0.5 times the values of WIOD. In this case, fossil RMC values are not affected. Furthermore, the fossil RMC values of Russia lie outside the funnel shape (EORA values 0.2 to 0.5 times the WIOD values) with biomass RMC results not being concerned. Finally, we identified a single data point located outside, which stands for the fossil RMC of Korea in 1997. Here, the EORA value is 4.3 times the WIOD value, which is also significantly higher than the EORA values of other years. All exceptions mentioned are marked in Figure 2 and/or represented as time series in Figure 5 and Figure 6. While the identification of reasons for individual cases of unusually high disagreement would go beyond the scope of this study, the occurrences must be kept in mind when it comes to statistical modelling.

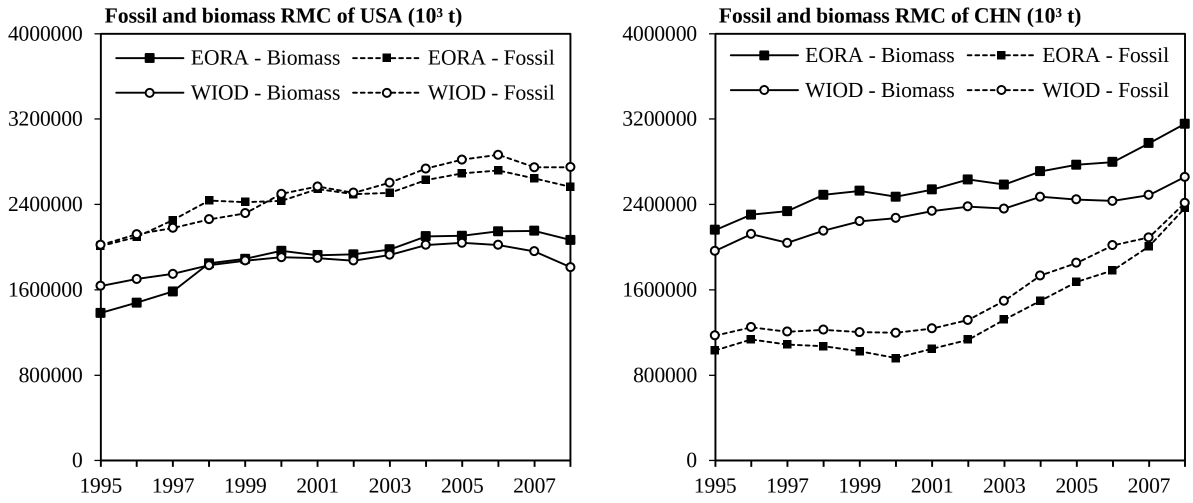

Figure 3: Comparison of time series convergence between WIOD and EORA regarding fossil and biomass raw material consumption (RMC) in thousands of metric tons (left-hand USA, right-hand China).

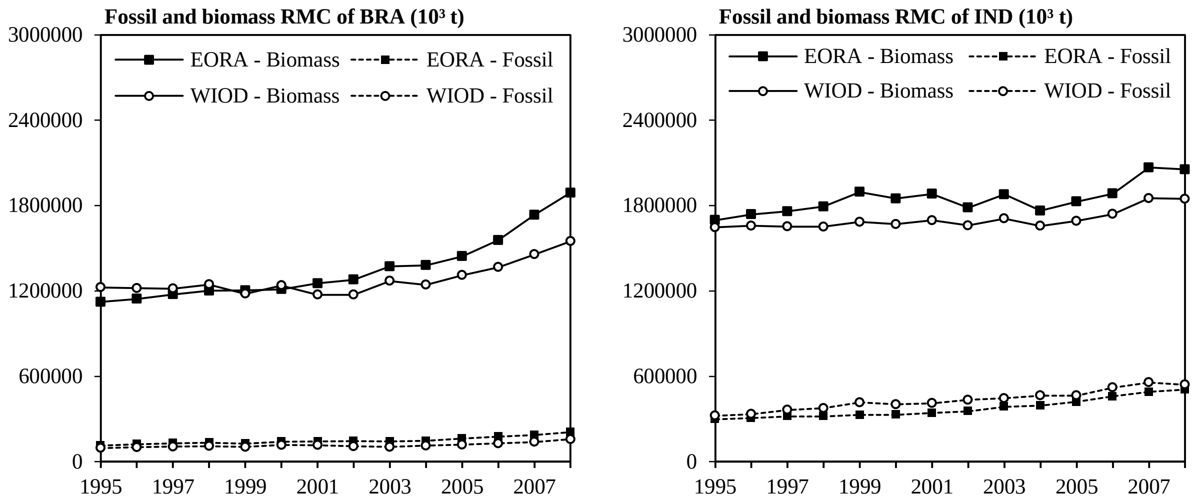

Figure 4: Comparison of time series convergence between WIOD and EORA regarding fossil and biomass raw material consumption (RMC) in thousands of metric tons (left-hand Brazil, right-hand India).

Figure 3 and Figure 4 display the fossil and biomass RMC convergence between WIOD and EORA for the largest economies in terms of their biomass RMC. According to the inter-model mean, USA, China, Brazil and India together account for about 43% of global biomass and 42% of global fossil RMC. WIOD and EORA exhibit a decent convergence for these countries regarding fossil and biomass RMC. The time series show low volatility and smooth behavior over years, which we interpret as an indication of high model robustness. Contentwise, the figures illustrate increases in RMC in all countries except USA, where a turnaround has been evident since 2006. Counter-tendencies between fossil and biomass RMC cannot be recognized, but rather an aligned behavior in most cases. Large country-specific differences are present regarding the ratio of fossil and biomass RMC. As the only one of the four economies, fossil RMC in the USA is above biomass RMC. In China, fossil RMC increased faster than biomass RMC since 2000, approximating its RMC composition that of highly industrialized countries. The opposite is true for Brazil, where biomass RMC accelerated faster from around 2000 onwards. Brazil and India show a significantly lower fossil RMC share than the USA and China.

Figure 5 and Figure 6 represent time series of the most important outliers and are therefore not interpreted contentwise. Instead, they are intended to shed light on the differences between WIOD and EORA results across time. In the case of Japan, WIOD and EORA results differ substantially for both, fossil and biomass RMC. In terms of their temporal dynamics the corresponding time series are partly similar. For Russia, WIOD derived fossil RMC is highly above EORA and, in contrast to Japan, the disagreement is time-variant. The Russian biomass RMC results demonstrate good convergence. In the case of Australia, biomass RMC values from WIOD are considerably higher than those from EORA. As for Japan, partial comparability is given in terms of temporal behavior. Recalling that smaller countries tend to feature worse convergences, the disparity between the Australian fossil RMC time series is in a usual range. Finally, the Korean fossil RMC time series includes a single data point in 1997, which is highly implausible in its context. The overall disagreement between the two fossil RMC time series is at the upper bound of the usual divergence range at this country size in terms of RMC. The Korean results related to biomass RMC are concordant.

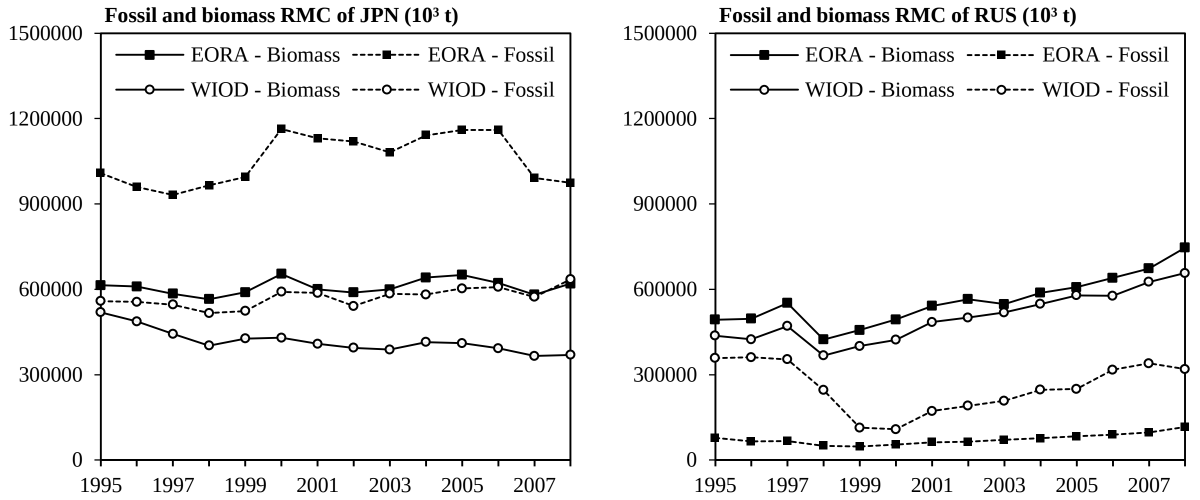

Figure 5: Comparison of time series convergence between WIOD and EORA regarding fossil and biomass raw material consumption (RMC) in thousands of metric tons (left-hand Japan, right-hand Russia).

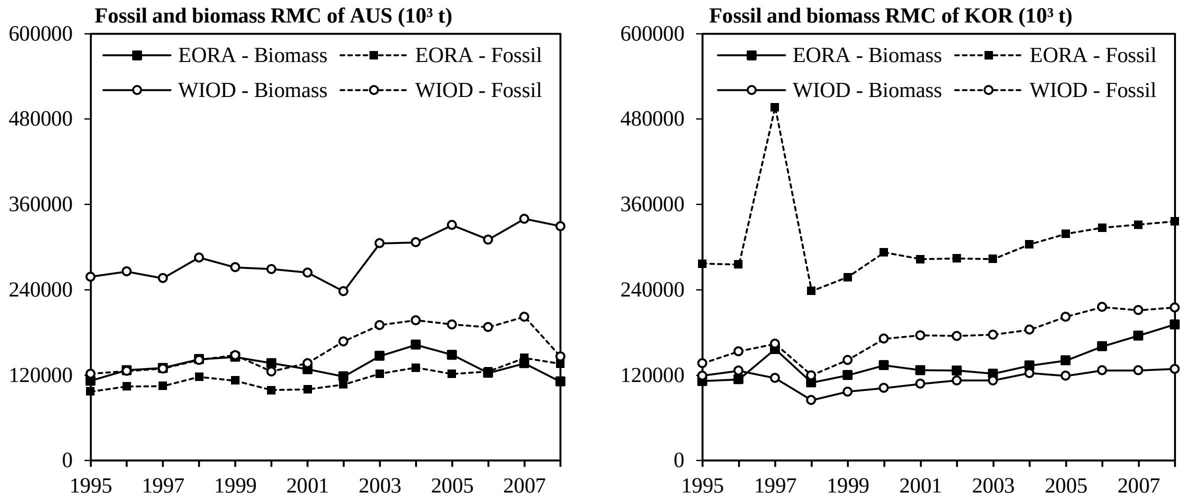

Figure 6: Comparison of time series convergence between WIOD and EORA regarding fossil and biomass raw material consumption (RMC) in thousands of metric tons (left-hand Australia, right-hand Korea).

Research on the causes of divergences in results from different input-output databases is currently going on. Moran and Wood (2014) investigated whether WIOD, EORA, and two other independently constructed MRIO databases converge when resulting carbon footprints are compared. They found that disagree between databases is typically lower than 10% for major economies if harmonized environmental extension data is used. Hence, despite of a range of different aggregation levels across the databases investigated, results tended to be similar suggesting that increased detail due to lower aggregation does not necessarily lead to better results. Furthermore, the authors discovered a relation between convergence and country size expressed in GDP or carbon emissions. In accordance with Moran and Wood, the results of this study present high convergence for large economies in terms of RMC. Given the complexity of constructing multi-regional input-output tables as well as the underlying differences between WIOD and EORA regarding assumptions, data sources and techniques (see section 3), the high convergence level is remarkable, particularly when focusing on the similarity of temporal dynamics. However, for smaller countries and some outliers discussed above, disagreement can be substantial. Owen et al. (2014) developed a structural decomposition-based method to attribute inter-model differences in results to the single components of an EEMRIO, namely to the input coefficient matrix (or to the Leontief inverse matrix), to final demand and to environmental extension data. Comparing WIOD and EORA using CO_2 emission data as extension, the authors found diverging results being caused by both, differences in the Leontief inverse and in final demand. Wieland et al. (2018) complemented existing approaches to assess inter-model differences by the so called structural production layer decomposition. Comparing WIOD and EORA (among other databases) they discovered domestic trade flows to be larger contributors to result variation than foreign trade flows. Hence, according to the findings of Owen et al. and Wieland et al., a first starting point for addressing the severe disagree in RMC results of Japan, Australia and Russia might be a comparison of their domestic inter-sectoral trade flows and their flows towards domestic final consumption across models. Due to the rather small temporal variance shown by the current analysis, such an investigation could be conducted focusing on a single year, reducing the involved datasets to a manageable size. This could unveil the “numerical cause” of divergence and possibly help to answer the question, why WIOD and EORA differ particularly strongly in these cases.

While research on the causes of deviating results derived from different input-output databases continues, our further work is concerned with the question, to what extent these inconsistencies influence regression-based explanations of RMC, in order to disclose their implications for a material-based indicator of bioeconomic transition.

5 Conclusions and Outlook

In order to measure and monitor progress towards bioeconomy, we propose to establish a material-based indicator. In this study we present a comparison of fossil and biomass raw material consumption (RMC) results derived from two independently constructed data sources (WIOD and EORA). As our results suggest, the principal convergence between WIOD and EORA regarding fossil and biomass RMC results is high enough to test, if inter-model differences have an appreciable impact on subsequent regression-based explanations of fossil and biomass RMC. Nonetheless, divergences may be high in some cases, which implies that individual absolute data points referring to a particular year and country should be interpreted with care. Taking advantage of an identified positive relation between convergence and country size, the sample needed for this task could be limited to large economies, hereby improving convergence of input data while keeping sample coverage losses as low as possible. In order to pursue the opportunity of a material-based indicator of bioeconomic transition further, we will construct two independent regression models, one using WIOD, the other EORA based RMC data as input. Drawing on explanatory variables such as population, affluence, consumption of energy from other than combustion and metabolic processes, domestic extraction of fossil resources, geographical zone/latitude and land cover, urbanization, and, if possible, on inequality, political and demographic structures, regulatory and cultural norms we will work on the following research questions.

- To which extent do inter-model differences (WIOD/EORA) in fossil and biomass RMC lead to differences in subsequent regression models?
- To which extent are the regression residuals sensitive to model choice (WIOD/EORA)?

We hypothesize that differences between the two regression models will be limited despite of disagreement in input data. On the other hand, we expect some countries not to be satisfactory explained by the models, as was the case in earlier studies. In this situation, a reasonably clear need – supported by two independent data sets – is demonstrated for a deeper investigation of the consumption patterns and drivers of the countries in question, which will help shaping a material-based indicator of bioeconomic transition.

Acknowledgements and Declarations

We would like to thank Christian Hofer and Yannick Oswald for their helpful comments. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors. The authors have no conflicts of interest to declare.

References

Beermann, M., Jungmeier, G., Pignatelli, Vito, Monni, Matteo, Van Ree, René, 2015. BioEconomy Strategies in the Member Countries of the IEA Bioenergy Implementing Agreement – current status, approaches and opportunities. Joanneum Research, Graz. http://www.ieabioenergy.com/wp-content/uploads/2015/06/Poster-BioEconomyStrategies.pdf. Accessed 28 March 2017.

Bithas, K., Kalimeris, P., 2017. Unmasking decoupling: Redefining the Resource Intensity of the Economy. The Science of the total environment 619-620, 338–351. 10.1016/j.scitotenv.2017.11.061.

Bruckner, M., Giljum, S., Lutz, C., Wiebe, K.S., 2012. Materials embodied in international trade – Global material extraction and consumption between 1995 and 2005. Global Environmental Change 22 (3), 568–576. 10.1016/j.gloenvcha.2012.03.011.

Budzinski, M., Bezama, A., Thrän, D., 2017. Monitoring the progress towards bioeconomy using multi-regional input-output analysis: The example of wood use in Germany. Journal of Cleaner Production 161, 1–11. 10.1016/j.jclepro.2017.05.090.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., Vries, G. de, 2013. The Construction of World Input-Output Tables in the WIOD Project. Economic Systems Research 25 (1), 71–98. 10.1080/09535314.2012.761180.

Eisenmenger, N., Wiedenhofer, D., Schaffartzik, A., Giljum, S., Bruckner, M., Schandl, H., Wiedmann, T.O., Lenzen, M., Tukker, A., Koning, A., 2016. Consumption-based material flow indicators — Comparing six ways of calculating the Austrian raw material consumption providing six results. Ecological Economics 128, 177–186. 10.1016/j.ecolecon.2016.03.010.

European Commission, 2012. Innovating for Sustainable Growth. A Bioeconomy for Europe. European Commission, Brussels, 64 pp.

Eurostat, 2007. Economy-wide Material Flow Accounts. A compilation guide.

Eurostat, 2013. Economy-wide Material Flow Accounts (EW-MFA). Compilation Guide 2013. http://ec.europa.eu/eurostat/documents/1798247/6191533/2013-EW-MFA-Guide-10Sep2013.pdf/. Accessed 25 March 2017.

FAO, 2016. How sustainability is addressed in official bioeconomy strategies at international, national, and regional leveles - An overview. Environment and Natural Resources Management Working Paper 63. FAO, Rome.

Genty, A., Arto, I., Neuwahl, F., 2012. Final Database of Environmental Satellite Accounts: Technical Report on their Compilation. WIOD Deliverable 4.6, Documentation. http://www.wiod.org/publications/source_docs/Environmental_Sources.pdf. Accessed 26 April 2018.

Giljum, S., Bruckner, M., Martinez, A., 2015. Material Footprint Assessment in a Global Input-Output Framework. Journal of Industrial Ecology 19 (5), 792–804. 10.1111/jiec.12214.

Hatfield-Dodds, S., Schandl, H., Newth, D., Obersteiner, M., Cai, Y., Baynes, T., West, J., Havlik, P., 2017. Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. Journal of Cleaner Production 144, 403–414. 10.1016/j.jclepro.2016.12.170.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., Fischer-Kowalski, M., 2009. Growth in global materials use, GDP and population during the 20th century. Ecological Economics 68 (10), 2696–2705. 10.1016/j.ecolecon.2009.05.007.

Krzyżaniak, M., Stolarski, M.J., Warmiński, K., 2018. Life cycle assessment of Virginia mallow production with different fertilisation options. Journal of Cleaner Production 177, 824–836. 10.1016/j.jclepro.2017.12.275.

Lenzen, M., Kanemoto, K., Moran, D., Geschke, A., 2012. Mapping the structure of the world economy. Environmental science & technology 46 (15), 8374–8381. 10.1021/es300171x.

Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building Eora: A Global Multi-region Input-output Database at High Country and Sector Resolution. Economic Systems Research 25 (1), 20–49. 10.1080/09535314.2013.769938.

Lutter, S., Lieber, M., Giljum, S., 2016. Global Material Flow database. Material extraction data. Technical Report, Version 2015.1. Institute for Ecological Economics, Vienna University of Economics and Business, Vienna. http://www.materialflows.net/fileadmin/docs/materialflows.net/WU_MFA_Technical_report_2015.1_final.pdf. Accessed 26 April 2018.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy 41 (6), 955–967. 10.1016/j.respol.2012.02.013.

Miller, R.E., Blair, P.D., 2009. Input-output analysis: Foundations and extensions, 2nd ed. Cambridge University Press, Cambridge.

Moran, D., Wood, R., 2014. Convergence between the EORA, WIOD, EXIOBASE, and OPENEU's Consumption-based Carbon Accounts. Economic Systems Research 26 (3), 245–261. 10.1080/09535314.2014.935298.

O'Brien, M., Wechsler, D., Bringezu, S., Arnold, K., 2015. Sachstandsbericht über vorhandene Grundlagen und Beiträge für ein Monitoring der Bioökonomie: Systemische Betrachtung und Modellierung der Bioökonomie. Wuppertal Institute, Wuppertal.

Owen, A., Steen-Olsen, K., Barrett, J., Wiedmann, T., Lenzen, M., 2014. A Structural Decomposition Approach to Comparing MRIO Databases. Economic Systems Research 26 (3), 262–283. 10.1080/09535314.2014.935299.

Pothen, F., 2017. A structural decomposition of global Raw Material Consumption. Ecological Economics 141, 154–165. 10.1016/j.ecolecon.2017.05.032.

Priefer, C., Jörissen, J., Frör, O., 2017. Pathways to Shape the Bioeconomy. Resources 6 (1), 10. 10.3390/resources6010010.

Pülzl, H., Kleinschmit, D., Arts, B., 2014. Bioeconomy – an emerging meta-discourse affecting forest discourses? Scandinavian Journal of Forest Research 29 (4), 386–393. 10.1080/02827581.2014.920044.

Ronzon, T., Lusser, M., Landa, L., M'Barek, R., Giuntoli, J., Cristobal Garcia, J., Parisi, C., Ferrari, E., Marelli, L., Torres de Matos, C., Gomez Barbero, M., Rodriguez Cerezo, E., 2017. JRC Science for Policy Report. Bioeconomy Report 2016. European Commission, Brussels.

Schaffartzik, A., Eisenmenger, N., Krausmann, F., Weisz, H., 2014. Consumption-based Material Flow Accounting. Journal of Industrial Ecology 18 (1), 102–112. 10.1111/jiec.12055.

Schaffartzik, A., Wiedenhofer, D., Eisenmenger, N., 2015. Raw Material Equivalents: The Challenges of Accounting for Sustainability in a Globalized World. Sustainability 7 (5), 5345–5370. 10.3390/su7055345.

Schandl, H., Turner, G.M., 2009. The Dematerialization Potential of the Australian Economy. Journal of Industrial Ecology 13 (6), 863–880. 10.1111/j.1530-9290.2009.00163.x.

Schandl, H., West, J., 2010. Resource use and resource efficiency in the Asia–Pacific region. Global Environmental Change 20 (4), 636–647. 10.1016/j.gloenvcha.2010.06.003.

Schoer, K., Weinzettel, J., Kovanda, J., Giegrich, J., Lauwigi, C., 2012. Raw material consumption of the European Union--concept, calculation method, and results. Environmental science & technology 46 (16), 8903–8909. 10.1021/es300434c.

Schoer, K., Wood, R., Arto, I., Weinzettel, J., 2013. Estimating raw material equivalents on a macro-level: comparison of multi-regional input-output analysis and hybrid LCI-IO. Environmental science & technology 47 (24), 14282–14289. 10.1021/es404166f.

Shao, Q., Schaffartzik, A., Mayer, A., Krausmann, F., 2017. The high 'price' of dematerialization: A dynamic panel data analysis of material use and economic recession. Journal of Cleaner Production 167, 120–132. 10.1016/j.jclepro.2017.08.158.

Steinberger, J.K., Krausmann, F., Eisenmenger, N., 2010. Global patterns of materials use: A socioeconomic and geophysical analysis. Ecological Economics 69 (5), 1148–1158. 10.1016/j.ecolecon.2009.12.009.

Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., Vries, G.J. de, 2015. An Illustrated User Guide to the World Input-Output Database: The Case of Global Automotive Production. Rev International Economics 23 (3), 575–605. 10.1111/roie.12178.

Wiedmann, T., Wilting, H.C., Lenzen, M., Lutter, S., Palm, V., 2011. Quo Vadis MRIO?: Methodological, data and institutional requirements for multi-region input–output analysis. Ecological Economics 70 (11), 1937–1945. 10.1016/j.ecolecon.2011.06.014.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proceedings of the National Academy of Sciences of the United States of America 112 (20), 6271–6276. 10.1073/pnas.1220362110.

Wieland, H., Giljum, S., Bruckner, M., Owen, A., Wood, R., 2018. Structural production layer decomposition: a new method to measure differences between MRIO databases for footprint assessments. Economic Systems Research 30 (1), 61–84. 10.1080/09535314.2017.1350831.

Wood, R., Lenzen, M., Foran, B., 2009. A Material History of Australia. Journal of Industrial Ecology 13 (6), 847–862. 10.1111/j.1530-9290.2009.00177.x.