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Monitoring the progress towards bioeconomy using multi-regional input-output analysis: The example of wood use in Germany

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ABSTRACT

The transition from a fossil-based economy towards a bioeconomy is supported and adopted by governments and intergovernmental organizations all over Europe. Multidisciplinary monitoring approaches that integrate social, environmental and technological perspectives are needed to promote the development of sustainable energy generation and sustainable production. An essential characteristic of a sufficient monitoring approach is the consideration of global impacts due to biomass use, whilst at the same time providing detailed differentiation between types and utilizations of biomass. To this date, comprehensive tools mapping the environmental and socio-economic impacts due to biomass use in a detailed as well as in a global manner are not available. For this reason, we demonstrate in this article how multi-regional input-output (MRIO) analysis can be used for the monitoring of the intended progress towards a bioeconomy. By taking the German wood-based economy in the year 2007 as a representative part of the German bio-based economy, we analyze it in terms of the eight goals of the German National Policy Strategy on Bioeconomy. We use the MRIO database EXIOBASE v2 and enhance the level of detail by disaggregating the most relevant German industries in terms of wood use. Indicator results can be deduced for six of the eight goals of the national strategy on bioeconomy. The quantification of the proposed indicators provides sector-specific as well as transnational insights of the German wood-based economy. Current limitations that restrict the applicability of MRIO analysis to monitor the development of the bioeconomy are discussed. In addition, potential ways to overcome these limitations are indicated.

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1. Introduction

The transition from a fossil-based economy towards a bioeconomy is supported and adopted by governments and intergovernmental organizations all over Europe (e.g., European Commission, 2012; Ministry of the Environment, 2014; Federal Ministry of Food and Agriculture, 2013). The strategies for achieving the vision of a bioeconomy are associated with several environmental and socio-economic goals such as climate protection, job creation, strengthening the innovation of the economy while preserving biodiversity and food security (Fund et al., 2015). However, to assess the achievement of these targets, the definition of quantifiable indicators is needed (O'Brien et al., 2017; Bosch et al., 2015). Furthermore, multidisciplinary approaches that integrate social, environmental and technological perspectives are necessary to promote the development of sustainable energy generation and sustainable production (Sáez-Martinez et al., 2016). Monitoring tools are crucial as a basis for political interventions, to detect feedstock limitations (cf., Hennig et al., 2016) and to identify undesirable developments and trade-offs (cf., Bezama, 2016). An essential characteristic of a sufficient monitoring approach is the consideration of global impacts due to biomass use (Searchinger et al., 2008). Furthermore, to cope with complexity and diversity of bio-based value chains within a bioeconomy (Gold and Seuring, 2011), the detailed differentiation between types and utilizations of biomass is needed. However, to this date comprehensive tools mapping the environmental and socio-economic impacts due to biomass use in a detailed as well as in a global manner are not available.

Detailed quantification of biomass flows is typically carried out using material flow balances. For example, Mantau (2015)

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determines material flows and cascade factors of wood in Germany and the EU using sectoral mass flow analysis. Carus et al. (2010), on the other hand, determine German biomass flows for material use. However, the quantification of physical flows seems not sufficient to monitor all of the comprehensive goals related to political strategies, due to the fact that neither environmental nor socio-economic impacts are assessed. For this reason, recent efforts in the field of input-output analysis have aimed at developing more detailed tables. Bösch et al. (2015a) present a physical input-output table of the German wood and paper flow, which shows the complete wood fiber flow throughout the German economy. Furthermore, Bösch et al. (2015b) economically evaluate the German forest-based industries using a disaggregated input-output table of Germany. The tables, which are developed in these studies, only represent Germany as the region under study. Thereby, interrelations with other countries are condensed to exports and imports of Germany without indicating what and where foreign impacts result. Hence, induced transnational impacts of biomass use cannot be considered in a sufficient manner.

Multi-regional input-output (MRIO) analysis has been becoming a rapidly growing field to assess inter-industrial and transregional human activity within natural ecosystems (Tukker et al., 2013; Peters and Hertwich, 2010; Lenzen et al., 2004). Essential for this method is that, by taking intercountry linkages into account, it gives a comprehensive picture of the flows of goods and services among industries. Data projects have been conducted to provide large IO databases for global models (Aguiar et al., 2016; Timmer et al., 2015; Wood et al., 2015; Lenzen et al., 2013). The EXIOBASE database illustrates the world's economy in 2007 by 48 regions a'163 industries (Wood et al., 2015). Supply and use tables, input-output tables and environmental intervention matrices are provided therein. This allows socio-economic and environmentally analyses on product-, industry-as well as country-specific levels (e.g., de Koning et al., 2016; Tukker et al., 2016, 2013). However, detailed analyses about specific biomass value chains is hindered using those databases, due to the aggregation of different commodities into product groups, i.e., the aggregation of bio-based and fossil-based products (cf., Hildebrandt et al., 2017).

In this article, we want to demonstrate how MRIO analysis can be used for the monitoring of the intended progress towards bio-economy. For this purpose, we analyze the wood-based economy as a representative part of the German bio-based economy in year 2007. The analysis is conducted in terms of the eight goals of the German National Policy Strategy on Bioeconomy (Federal Ministry of Food and Agriculture, 2013). Therefore, we disaggregate the wood-relevant German industries of the EXIOBASEv2 model and determine proposed socio-economic and environmental indicator results based on multi-regional input-output analysis. Finally, we discuss limitations that currently restrict the applicability of MRIO analysis to monitor the development of a bioeconomy.

2. Methods

2.1. Basic modeling

The basic input-output model includes a quantity model and a price model. The quantity model (Equation (1)) describes the track of goods and services throughout the economy.

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

x is the vector of total output, **y** the households demand vector, **A** the technical coefficient matrix and **I** the identity matrix of **A**. The technical coefficient matrix expresses the inputs of each process as a fraction of its output ($\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1}$). The price model determines the unit prices of the industrial outputs (Equation (2)).

$$\mathbf{p}' = \mathbf{v}'(\mathbf{I} - \mathbf{A})^{-1} \tag{2}$$

p and **v** are the vectors of unit prices and value-added per unit of output, respectively. The environmental extension can be done by using the environmental intervention matrix **E**, which includes interventions such as land use and GHG emissions, e.g., to determine the production-based impacts within an economy (Equation (3)).

$$\mathbf{e}' = \mathbf{E}\widehat{\mathbf{x}}^{-1} \tag{3}$$

2.2. Disaggregation of German wood-based sectors

In order to build up the overall picture of wood use in Germany,

Table 1
Structure of supply and use framework including the disaggregation principle (bold matrix elements belongs to the aggregated industry that is finally deleted from the matrices).

	Commodities	Industries	Final demand	Total output
Commodities		$\mathbf{U}$: $\begin{bmatrix} u^*_{1,1} & \mathbf{u^*_{1,N+1}} \to u_{1,2} & \cdots & u_{1,1+n} \\ u^*_{2,1} & \mathbf{u^*_{2,N+1}} \to u_{2,2} & \cdots & u_{2,1+n} \\ \mathbf{u^*_{M+1,1}} & \mathbf{u^*_{M+1,2}} \searrow & & \\ \downarrow\ u_{3,1} & u_{3,2} & \cdots & u_{3,1+n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{2+m,1} & u_{2+m,2} & \cdots & u_{2+m,1+n} \end{bmatrix}$	$\mathbf{f}$: $\begin{bmatrix} f^*_1 \\ f^*_2 \\ \mathbf{f^*_{M+1}} \\ \downarrow\ f_3 \\ \vdots \\ f_{2+m} \end{bmatrix}$	$\mathbf{q}$
Industries	$\mathbf{V}$: $\begin{bmatrix} v^*_{1,1} & v^*_{1,2} & \mathbf{v^*_{1,M+1}} \to v_{1,3} & \cdots & v_{1,2+m} \\ \mathbf{v^*_{N+1,1}} & \mathbf{v^*_{N+1,2}} & \mathbf{v^*_{N+1,M+1}} \searrow & & \\ \downarrow\ v_{2,1} & \downarrow\ v_{2,2} & v_{2,3} & \cdots & v_{2,2+m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ v_{1+n,1} & v_{1+n,2} & v_{1+n,3} & \cdots & v_{1+n,2+m} \end{bmatrix}$			$\mathbf{x}$
Value added		$\mathbf{v}'$: $\begin{bmatrix} v^*_{k,1} & \mathbf{v^*_{k,N+1}} \to v_{k,2} & \cdots & v_{k,1+n} \end{bmatrix}$		
Total input	$\mathbf{q}'$	$\mathbf{x}'$		

we disaggregated relevant German sectors of the EXIOBASE v2 input-output database, following the suggestion of Lenzen (2011) ("disaggregation, even if based on few data points, is superior to aggregating data in determining input-output multipliers"). For this purpose, many procedures of disaggregation have been developed (Wood et al., 2014; Lindner et al., 2012; Joshi, 2000; Wolsky, 1984).

In this study, we carried out the disaggregation using supply and use tables (SUTs) as proposed by Vendries Algarin et al. (2015). Table 1 shows the general principle of the disaggregation using the supply and use framework. Let **V** describe the same supply matrix as the original supply matrix **V*** and let **U** be the same use matrix as the original use matrix **U*** with the only difference being that the last industry ($N + 1$) and the last commodity ($M + 1$) is disaggregated into n sub-industries and m sub-commodities, respectively. The supply matrix **V** represents the produced commodities j by a certain industry i. The use matrix **U** illustrates the commodities that are used by a certain industry. Table 1 also exemplarily illustrates the disaggregation procedure for original supply and use matrices that contain three commodities and two industries. Industry $i = N{+}1$ is disaggregated into n new industries. These n industries supply und use m new commodities out of the original commodity $j = M{+}1$ that is supplied and used by the aggregated industry. The results of the disaggregation would be a new matrix **V** of the size of $(N + n) \times (M + m)$ and a new matrix **U** of the size of $(M + m) \times (N + n)$ compared with the original matrices $\mathbf{V}^{*}_{(N+1)\times(M+1)}$ and $\mathbf{U}^{*}_{(M+1)\times(N+1)}$.

In the work of Vendries Algarin et al. (2015), the authors recommend a default procedure and a detailed manual procedure to allocate the supplied and used commodities of the original industry to new disaggregated industries. The default procedure is applied to industries, for which no detailed information can be collected. Here, for the default procedure we used production mix percentages to allocate the used and supplied commodities of the original aggregated industry. On the other hand, for detailed manual allocation, we used several sources of data such as market information and LCI data for wood products. LCI data from Rüter and Diederichs (2012) was taken to allocate certain commodities, such as electricity, natural gas, metals and wood products, to the sub-industries. In this latter work, the authors provide comprehensive LCI data for various wood products in physical units, which we transformed into monetary units by using conversion factors based on statistical price data (e.g., DESTATIS, 2008a). The manual procedure was completed by the use of market information. Specific information about the product flows (BMEL, 2010; Mantau and Bilitewski, 2010) was collected to identify the destiny of disaggregated commodities. Table 2 identifies the collected data that was used to generate the disaggregated SUTs.

To finalize the disaggregation, we also adjusted the vectors of final demand **f** and value added **v'**. The total output x of each industry i can be obtained by summing the row entries of the supply matrix ($\sum_j v_{ij}$). By knowing the values for **U** and **x,** the total value added per industry can be calculated, due to $\sum_j u_{ji} + \sum_k v_{ki} = x_i$. This adjustment ensures that the balance between production and consumption of commodities is fulfilled (Miller and Blair, 2009). The challenge is to detect the different categories k of value added of the disaggregated industries. The category $v_{labor,i}$ can be determined using statistical information about the number of employees. The other components of value added k (capital, tax and surplus) of the disaggregated industries were determined by the assumption that the percentages of these parts of value added are the same as in the aggregated industry. The total output q of each commodity j can be calculated by the summation of the row entries of the supply matrix ($\sum_i v_{ij}$). By using the determined vector, it is possible to calculate the final demand **f** of commodities, because of $q_j = \sum u_{ji} + f_j$. Emissions, materials and resources per Euro's worth of disaggregated industry output were assumed to equal those per Euro's worth of aggregated industry output. The whole procedure was carried out sequentially for each German wood-relevant sector that had to be disaggregated. Other sectors of Germany and sectors of other countries remained untouched. The new matrices **U**, **S'**, **q**, **x** and **f**, hence, could be determined without violating accounting rules in terms of the production balance (cf., Majeau-Bettez et al., 2016).

The disaggregated supply and use tables were used to create a new symmetric technical coefficient matrix **A.** We used the so-called industry-technology assumption. Thereby, every industry is regarded as representing a unique technology that converts a bunch of multiple inputs into a bunch of multiple products (cf., Majeau-Bettez et al., 2014). Equation (4) represents the calculation of technical coefficients by means of the SUTs (Miller and Blair, 2009). By disaggregating the sectors of the original EXIOBASE, we increased the level of detail by 20–33 German wood-based industries.

$$\mathbf{A}^{I}_{i\times i} = \left[\mathbf{V}\hat{\mathbf{q}}^{-1}\right]\left[\mathbf{U}\hat{\mathbf{x}}^{-1}\right] \tag{4}$$

2.3. Indicator selection

The political motivation for promoting the transition of the fossil-based economy into a bio-based economy is associated with several goals that are formulated in political strategies on bioeconomy. Fund et al. (2015) concludes that "across most countries, bioeconomy development is motivated by meeting the grand societal challenges, such as climate change mitigation, food security and sustainable resources management". Our selection of indicators is carried out in accordance to the German National Policy Strategy on Bioeconomy (Federal Ministry of Food and Agriculture, 2013). This strategy formulates the following eight goals:

1. Secure supply of food to the population in Germany and the world
2. Transition to an economy that is based on renewable resources
3. Long term security of renewable resources
4. Sustainable use of renewable resources while conserving biodiversity and soil fertility
5. Protection of the climate
6. Strengthening of Germany's innovation and competitiveness
7. Securing and creating employment and value added
8. Sustainable consumption on the part of consumers

In the next sections, we determine and discuss indicator results based on MRIO analysis for the year 2007 and identify current limitations that hinder to address all goals of the strategy.

3. Results

Table 3 provides a set of indicators, which can be potentially determined for the monitoring towards a bio-based economy. Several goals can be well-addressed using the input-output framework and current available data. Exemplary indicator results could be determined for six of the eight goals of the German Bioeconomy strategy: *change to a bio-based economy*, *long term security*, *climate protection*, *innovation and competitiveness*, *jobs and value added* and *sustainable consumption*. However, indicators for *food security* and *biodiversity and soil fertility* could not be determined due to insufficient data availability. The proposed list of indicators makes no claim to be complete. Rather, the aim is to

Table 2
Disaggregated EXIOBASE industries of Germany. "~" indicates that a disaggregation of the EXIOBASE industry was not necessary.

EXIOBASE industry	No.	Disaggregation	Production share of aggregated industry [%]	Reference	Additional information
Forestry, logging and related service activities	1	Softwood, fuelwood	6.97	Calculation based on Seintsch (2011) and BMEL (2010)	Manual allocation of use table row entries for *Manufacture of wood and of products of wood and cork, except furniture, manufacture of articles of straw and plaiting materials*, *Pulp*, *Paper*, *Production of electricity by biomass and waste* based on BMEL (2010) and Mantau and Bilitewski (2010).
	2	Softwood, pulpwood	13.29		
	3	Softwood, logwood	47.40		
	4	Hardwood, fuelwood	7.36		
	5	Hardwood pulpwood	2.51		
	6	Hardwood, logwood	2.17		
	7	Forestry others	20.30		
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	8	Sawmill industry	27.50	DESTATIS (2008a)	Manual allocation of supply table column entries according to Mantau and Bilitewski (2010) and reasonable assumptions. Use of LCI data (Rüter and Diederichs, 2012) to allocate use table column entries
	9	Fiberboard industry	12.60		
	10	Particle board industry	13.49		
	11	Plywood (incl. veneer) industry	3.65		
	12	Parquet industry	1.64		
	13	Pellet industry	0.41		
	14	Timber structures industry	2.67		
	15	Wooden windows industry	4.56		
	16	Wooden doors industry	3.91		
	17	Prefabricated buildings	8.12		
	18	Pallets industry	3.47		
	19	Other wood processing industry	17.99		
Manufacture of furniture; manufacturing n.e.c.	20	Wood-based furniture industry	46.22	DESTATIS (2008a)	Manual allocation of use table column entries for *forestry* and *manufactured wood products*, *rubber and plastic products* and *fabricated metal products*.
		Other furniture industry	53.78		
Publishing, printing and reproduction of recorded media	21	Printing and publishing industry	89.55	DESTATIS (2008a)	Manual allocation of use table column entries for *paper and pulp products* and *plastics, basics*.
		Reproduction of other recorded media	10.45		
Construction	22	Wood-based construction industry	6.97	DESTATIS (2008b)	Manual allocation of use table column entries for *forestry*; *manufactured wood products; stone*, *sand and clay*, *cement*, *lime and plaster*, *ceramic goods* and *bricks, tiles and construction products*.
		Other construction industry	93.03		
Pulp industry	23	~			
Paper industry	24	~			
Re-processing of secondary paper into new wood pulp	25	~			
Re-processing of secondary wood into new wood material	26	~			
Electricity from biomass and waste	27	~			
Incineration of waste: wood	28	~			
Incineration of waste: paper	29	~			
Biogasification of paper, incl. land application	30	~			
Composting of paper and wood, incl. land application	31	~			
Landfill of waste: Paper	32	~			
Landfill of waste: Wood	33	~			

illustrate the broadness of analysis that can be done using MRIO analysis.

To enhance clarity, the illustration of the indicator results according to the goals of the Bioeconomy strategy is rearranged within the following sections. The results are demonstrated starting with goal 3 and followed by goals 2, 7, 6, 8 and 5.

3.1. Long-term security of renewables (Goal 3)

To maintain functioning forest ecosystems, Sustainable Forest Management (SFM) principles have been implemented by many countries all over the globe (FAO, 2016). In Germany, principles of SFM date back to the 17th century. However, implementing SFM principles does not immediately lead to less deforestation in developing countries (Brandt et al., 2016; Cerutti et al., 2008). To answer the question if long-term security of renewable resources is guaranteed, it is all the more important that origin and quantity of biomass are known. Weimar (2011) quantified German wood flows as wood fiber equivalents. Wood fiber equivalent is a unit that describes the equivalent volume of wood fibers (at the fiber saturation point), which is contained in a certain product. This unit allows the detection of material flows among various utilizations; it was used by Bösch et al. (2015b) to determine a physical input-output table for Germany. We followed the approach and calculated fiber equivalents [m^3(f)] for all wood-based industries (Table 4). Furthermore, the equivalents of German wood-based industries were used to calculate the equivalents of aggregated industries of foreign countries.

Fig. 1 illustrates origins and destinies of imported and exported wood products of Germany expressed in m^3 of wood fiber equivalents. Imports of wood-based products to Germany are 97.7 Mm^3(f). Exports from Germany to foreign countries are 85.9 Mm^3(f). Hence, a physical trade deficit at 11.9 Mm^3(f) results. Imports from Sweden at 18.9 Mm^3(f) have the highest contribution

Table 3
Proposed indicators for a monitoring.

Goals of national policy strategy	Indicators of case study	Formulation	Multi-regional IO needed?	Disaggregation needed?
Goal 1: Food security of Germany and the world	–	Principally possible, but not addressed due to data gaps	–	–
Goal 2: Change to bio-based economy	Contribution to value added Contribution to employment	$\frac{v_{ki}}{\sum_i v_{ki}} \forall i \in Germany$	No	Yes
Goal 3: Long term security of renewables	Physical balance of trade	$export - import$ [m^3 *wood fiber equivalent*]	No	Yes
Goal 4: Biodiversity and soil fertility	–	Principally possible, but not addressed due to data gaps	–	–
Goal 5: Climate protection	GHG emissions of Germany (production-based)	$\mathbf{e}' = \mathbf{E}\hat{\mathbf{x}}^{-1}$	Yes	No
	GHG emissions of Germany (consumption-based)	$\mathbf{u}' = (\mathbf{e}'\hat{\mathbf{x}}^{-1})(\mathbf{I} - \mathbf{Z}\hat{\mathbf{x}}^{-1})^{-1}\hat{\mathbf{y}}$		
	GHG emissions of Germany (income-based)	$\mathbf{d} = \hat{\mathbf{v}}(\mathbf{I}^{-1} - \hat{\mathbf{x}}^{-1}\mathbf{Z})^{-1}(\hat{\mathbf{x}}^{-1}\mathbf{e})$		
Goal 6: Innovation and competitiveness	Forward linkage	$U^g_{i\cdot} = \left(\sum_j \frac{v_i}{v} G_{ij}\right) \Big/ \left(\frac{1}{N}\sum_{ij} \frac{v_i}{v} G_{ij}\right)$	No	Yes
	Backward linkage	$U^l_{\cdot j} = \left(\sum_i \frac{v_i}{y} L_{ij}\right) \Big/ \left(\frac{1}{N}\sum_{ij} \frac{v_i}{y} L_{ij}\right)$		
Goal 7: Jobs and value added	Same as of Goal 2		No	Yes
Goal 8: Sustainable consumer consumption	Forest land use due to consumption GHG emissions due to consumption (cf., Goal 5)	$\mathbf{u}' = (\mathbf{e}'\hat{\mathbf{x}}^{-1})(\mathbf{I} - \mathbf{Z}\hat{\mathbf{x}}^{-1})^{-1}\hat{\mathbf{y}}$	Yes	No

to the wood imports of Germany. The majority of this import flow is determined by paper products. Other important regions of German wood imports are Rest of Africa (WA), China (CN), Poland (PL), Austria (AT) and Czech Republic (CZ). On the other hand, most important export regions are CN, AT and the Netherlands (NL).

The exports of wood fiber are about 12% lower than the imports of Germany. For the year 2011 Bösch et al. (2015b) quantified the import volume at 67.0 Mm^3(f) and an export volume at 60.4 Mm^3(f), indicating that exports are about 10% lower than imports. Thus, it seems that Germany is a net importer of wood fibers. The indicator gives a generic evaluation of the total amount of wood flows. For more comprehensive conclusions, detailed analysis of product-specific flows is necessary. This is possible, but due to the exemplary character of this study we focus on the generic illustration.

3.2. Change to bio-based economy (Goal 2) and jobs and value added (Goal 7)

The change to a bio-based economy is supported in many countries. To analyze the role of a bio-based economy, several indicators, such as turnover, value added, number of enterprises and employees, can be determined (Scarlat et al., 2015). In this study, we quantified the contributions of wood industries to the total value added and to the total employment in Germany.

The creation of jobs and value added is closely connected to well-being. From a government's perspective the general aim might be to enhance labor and taxes. Whereas, the aim of companies is usually to reduce certain components of value added (i.e., labor and taxes) while maximizing profit. The total contribution of wood-based industries to the German value added is 2.42% (Fig. 2), which equates to 54.9 bn €. *Publication and printing industry of paper-based media* contributes most at 0.91% (20.6 bn €). With a higher distance *pulp industry*, *wood-based furniture industry*, *paper industry* and *sawmill industry* follow, at 0.20% (4.5 bn €), 0.20% (4.5 bn €), 0.17% (3.8 bn €) and 0.16% (3.6 bn €), respectively. The indicator results for contribution to total German employment show a similar picture. The overall contribution of wood-based industries is about 1.48% (556,948 employees).

Table 4
Wood fiber equivalents per output of German wood-based industry (rounded).

No.	Industry	Wood fiber equivalent [m^3(f)/1000€]
1	Softwood, fuelwood	28.57
2	Softwood pulpwood	25.00
3	Softwood, logwood	16.67
4	Hardwood, fuelwood	28.57
5	Hardwood, pulpwood	25.00
6	Hardwood, logwood	16.67
7	Forestry others	0.00
8	Sawmill industry	7.30
9	Fiberboard industry	3.95
10	Particle board industry	5.97
11	Plywood (incl. veneer) industry	1.18
12	Parquet industry	2.47
13	Pellet industry	43.21
14	Timber structures industry	9.39
15	Wooden windows industry	0.85
16	Wooden doors industry	1.32
17	Prefabricated buildings	0.67
18	Pallets industry	4.05
19	Other wood processing industry	2.89
20	Wood-based furniture industry	0.96
21	Printing and publishing industry	0.26
22	Wood-based construction industry	1.43
23	Pulp industry	1.70
24	Paper industry	3.12
25	Re-processing of secondary paper into new wood pulp	1.70
26	Re-processing of secondary wood into new wood material	2.89
27	Electricity from biomass and waste	0.00
28	Incineration of waste: wood	0.00
29	Incineration of waste: paper	0.00
30	Biogasification of paper, incl. land application	0.00
31	Composting of paper and wood, incl. land application	0.00
32	Landfill of waste: Paper	0.00
33	Landfill of waste: Wood	0.00

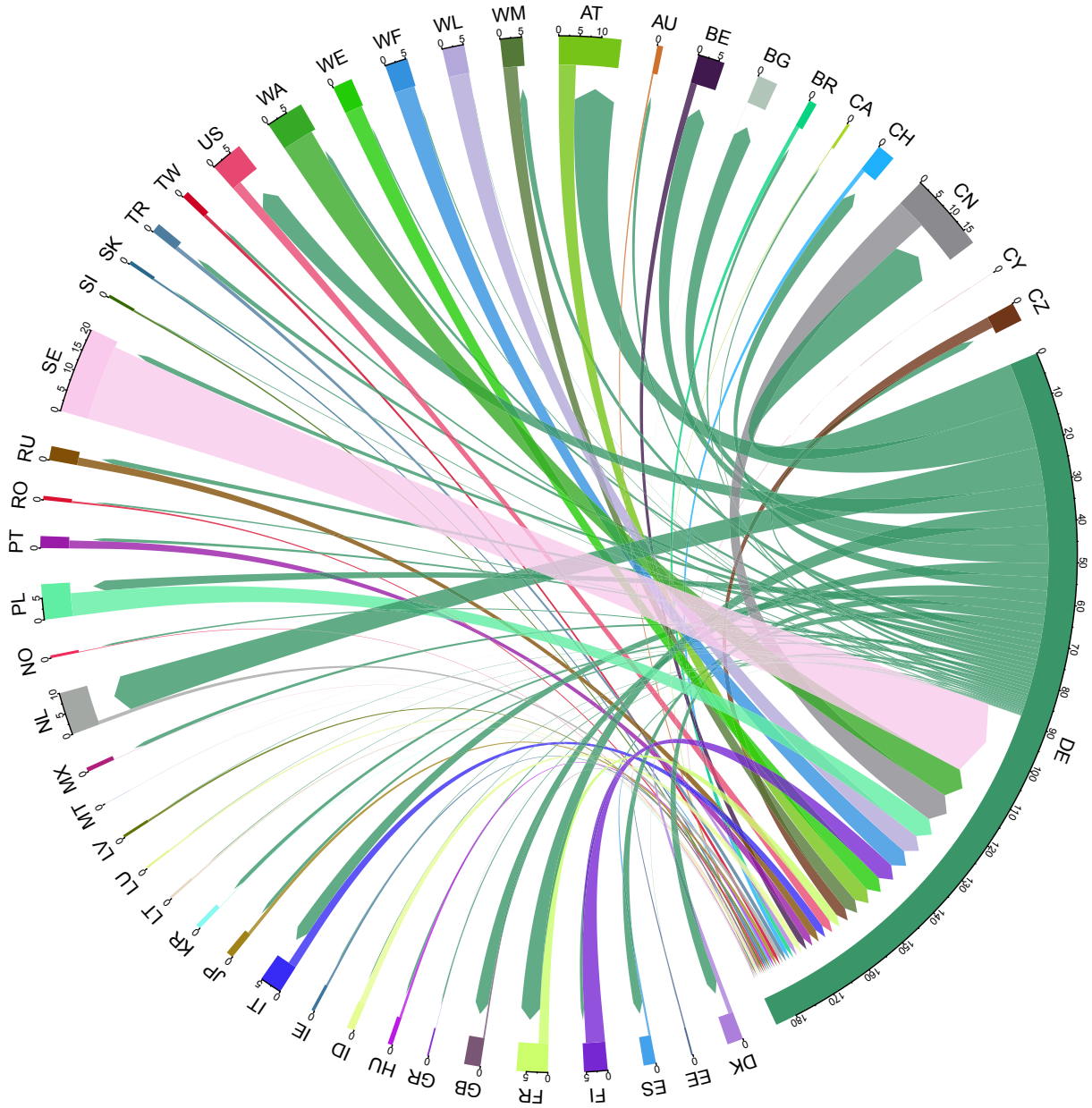


Fig. 1. Foreign wood fiber trade [Mm^3 fiber-eq.] of Germany in 2007. Jade green arrows illustrate exports of Germany to a foreign country; other colored arrows illustrate imports of Germany from a foreign country. The physical balance of trade can be determined by subtracting the sum of all imports from the sum of all exports. DE: Germany, CZ: Czech Republic, CY: Cyprus, CN: China, CH: Switzerland, CA: Canada, BR: Brasil, BG: Bulgaria, BE: Belgium, AU: Australia, AT: Austria, WM: RoW Middle East, WL: RoW America, WF: RoW Africa, WE: RoW Europe, WA: RoW Asia and Pacific, US: USA, TW: Taiwan, TR: Turkey, SK: Slovakia, SI: Slovenia, SE: Sweden, RU: Russia, RO: Romania, PT: Portugal, PL: Poland, NO: Norway, NL: Netherlands, MX: Mexico, MT: Malta, LV: Latvia, LU: Luxembourg, LT: Lithuania, KR: South Korea, JP: Japan, IT: Italy, IE: Ireland, ID: Indonesia, HU: Hungary, GR: Greece, GB: Great Britain, FR: France, FI: Finland, ES: Spain, EE: Estonia, DK: Denmark.

The results indicate that the wood-based industries play a minor role for the total German economy in 2007. To achieve progress in regard to the change to a bio-based economy, it is clear that the contribution of bio-based industries to the German value added has to be increased. The utilization of biomass by biorefineries has been identified as a cornerstone of a bioeconomy (The Federal Government, 2012). Several concepts, such as lignocellulosic biorefineries, have been developed that are suitable to support the transition of the chemical sector (e.g., Nitzsche et al., 2016; Zech et al., 2016). However, to foster these technologies, economic and political challenges have to be addressed (Hellsmark et al., 2016).

The quantification of the contributions to value added and employment only include the direct effects of wood use. Several other upstream and downstream industries can be dependent on wood-based industry. These aspects are not considered here; but it can be addressed via other indicators such as forward and backward linkage (Goal 6, Section 3.4).

3.3. Innovation and competitiveness (Goal 6)

Wood and Hertwich (2013) discuss the need for systemic measures in terms of life cycle sustainability assessment (LCSA). To address innovation, the authors propose the use of linkage indicators as a measure of production complexity. Forward linkage measures the importance of a product for other sectors that process this product. Backward linkage measures the importance of

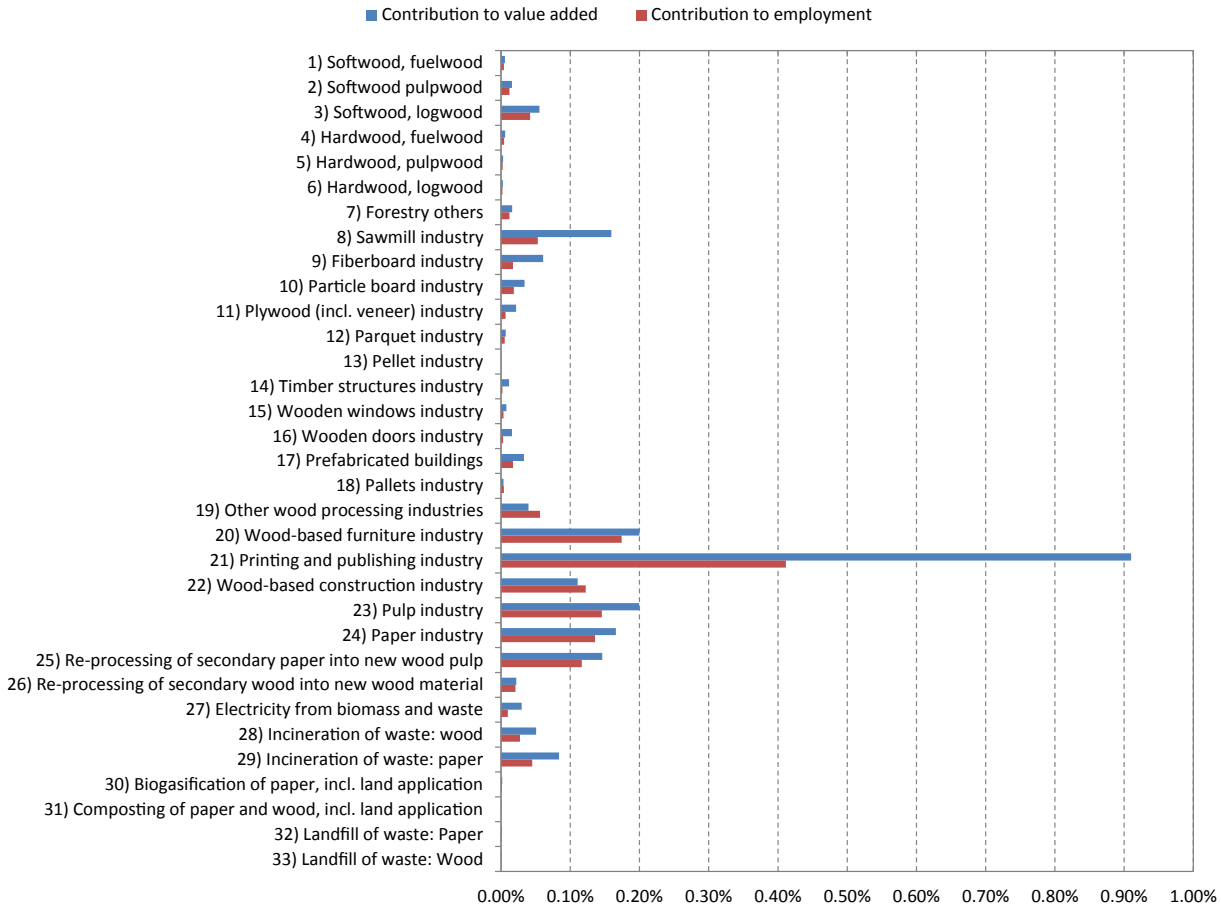


Fig. 2. Contribution to German value added and employment.

operating a technology for other products that are processed by this technology.

We follow Wood and Lenzen (2009) determining measures for forward linkage $U_{i\cdot}^{g}$ and backward linkage $U_{\cdot j}^{l}$ based on the Ghosh inverse $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1}$ and the Leontief inverse $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$, respectively, where $\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{Z}$ and $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$. The row sums of the Leontief inverse ($\sum l_{ij}$) and the Ghosh inverse ($\sum g_{ij}$) are weighted by final demand $\hat{y}$ and value added v, respectively. Furthermore, normalization in terms of global averages is carried out to allow comparisons between industries (Lenzen, 2003). Key sectors are those that have strong normalized forward and backward linkage to other sectors of the economy ($U > 1$).

Table 5 illustrates the indicator results for the German wood-based industries. It is visible that 1 of the 33 assessed wood-based industries can be referred in year 2007 to be a key sector: *publishing and printing of paper-based media* with a forward linkage at 4.99 and a backward linkage at 3.86. Comparing the values of the wood-based industries to very important key sectors of Germany that are currently based on fossil resources or for those predominantly fossil resources are used during the operation of the product, helps us to interpret the results. For example, *plastics* and *manufacture of motor vehicles* have forward linkages of 18.50 and 15.14, respectively, and backward linkages of 26.50 and 100.85, respectively. On the way towards a bio-based economy it is crucial that biomass using industries increase its relative importance for the whole economy. However, upper limits for the sustainable use of biomass exist. Recalling the determined physical trade deficit at 11.9 Mm^3(f) in Section 3.1 and assuming a potential utilization of unused residues of forestry and wood industries in Germany at 9.5–24.9 million MG dry matter (Brosowski et al., 2016), which corresponds to 22.7–59.5 Mm^3(f), it seems very challenging to push other wood-based industries further towards key sectors of the economy.

3.4. Climate protection (Goal 8) and sustainable consumption (Goal 5)

Climate protection is an important goal in terms of a bio-based economy. In this study, we have decided to determine the total emissions irrespective of a sectorial level. Since the transition towards a bio-based economy is particularly argued by a reduction of greenhouse gas (GHG) emissions (e.g., Ingrao et al., 2016; Federal Ministry of Food and Agriculture, 2013; The Federal Government, 2012), one should expect a reduction of economy-wide emissions. The assessment on solely sectoral levels would not be sufficient to monitor the goal of an overall reduction of GHGs, due to the fact that reductions in a certain industry do not imply a reduction of overall emissions. Even so, sectorial assessments would be valuable to complement a monitoring in the manner that improvements of certain industries can be monitored.

Responsibilities for GHG emissions can be taken on from different perspectives (Marques et al., 2012). Besides the common approach to determine production-based emissions, which arise on the territory of a country, further metrics can be used. By applying the consumption-based perspective, emissions that are necessary to produce a country's final demand for products and services are taken into account. Seeking to lower impacts per consumption of capita can be interpreted as a “sufficiency strategy” towards a

Table 5
Indicator results for innovation and competitiveness (Goal 6) of German wood-based industries.

No.	Industry	Backward linkage	Forward linkage
1	Softwood, fuelwood	0.00	0.04
2	Softwood pulpwood	0.01	0.13
3	Softwood, logwood	0.05	0.42
4	Hardwood, fuelwood	0.00	0.04
5	Hardwood, pulpwood	0.00	0.02
6	Hardwood, logwood	0.00	0.02
7	Forestry others	0.01	0.11
8	Sawmill industry	0.16	1.06
9	Fiberboard industry	0.03	0.35
10	Particle board industry	0.04	0.21
11	Plywood (incl. veneer) industry	0.01	0.13
12	Parquet industry	0.00	0.04
13	Pellet industry	0.00	0.00
14	Timber structures industry	0.00	0.07
15	Wooden windows industry	0.01	0.05
16	Wooden doors industry	0.01	0.09
17	Prefabricated buildings	0.01	0.18
18	Pallets industry	0.00	0.02
19	Other wood processing industry	0.04	0.22
20	Wood-based furniture industry	0.69	0.65
21	Printing and publishing industry	3.86	4.99
22	Wood-based construction industry	0.54	0.36
23	Pulp industry	0.06	1.81
24	Paper industry	0.47	1.15
25	Re-processing of secondary paper into new wood pulp	0.03	1.33
26	Re-processing of secondary wood into new wood material	0.01	0.13
27	Electricity from biomass and waste	0.02	0.19
28	Incineration of waste: wood	0.04	0.23
29	Incineration of waste: paper	0.08	0.44
30	Biogasification of paper, incl. land application	0.00	0.01
31	Composting of paper and wood, incl. land application	0.00	0.01
32	Landfill of waste: Paper	0.00	0.01
33	Landfill of waste: Wood	0.00	0.00

sustainable economy (Alcott, 2008). In contrast to efficiency strategies, where the aim is to use little as possible resources and to produce little as possible environmental impacts, the principle of sufficiency is to consume only that much, which is necessary for a healthy and happy life. In a third approach, income-based emissions can be determined that are enabled by suppliers; and that are necessary to provide a country's income (taxes, wages, profits). The focus of countries to reduce emissions taking on the production-based responsibility would neglect that for a global reduction further responsibilities can be important, i.e., the consumption-based perspective (Tukker et al., 2016). Hence, different metrics should be used for the allocation of environmental burdens in MRIO (cf., Dietzenbacher, 2005). In this study, we calculate the amount of carbon dioxide for all three responsibilities. Furthermore, we calculate the forest land use of Germany from different perspectives of responsibility and compare the results to other countries and regions of the model.

The contributions of Germany to global CO_2 emissions taking on the production-based, consumption-based and income-based responsibilities are 2.86% (8.56E+03 kg/capita/year), 3.18% (9.51E+03 kg/capita/year) and 3.64% (1.09E+04 kg/capita/year), respectively (Fig. 3a). The global average of CO_2 emissions in 2007 is 3.75E+03 kg per capita. There are not many countries in Europe that are below this value, for instance Romania's production-based and income-based responsibility. However, to achieve the target of 2 °C, CO_2 emissions should be gradually reduced until 2050 and should not exceed 1.10E+13 kg per year (van Vuuren et al., 2011). This means that CO_2 emissions must be about 1.13E+03 kg per capita in 2050, regardless of the accounting perspective. The 2 °C target is highly ambiguous; de Koning et al. (2016) conclude that the sole focus on technological efficiency improvements is not sufficient to meet this target.

In terms of forest land use, Fig. 3b shows that the global average forest land use is 6.17E-03 km^2 per capita per year. Remarkably, the production-based and income-based forest land use in Germany is 1.26E-03 km^2 per capita per year and 4.72E-03 km^2 per capita per year, respectively, while the consumption-based perspective accounts for 6.99E-03 km^2 per capita per year. From the results, which are in agreement with the results made in Section 3.1, it can be concluded that Germany induces a relatively high forest land use in foreign countries compared to the forest land use directly within the country.

Besides the current international climate policy that centers production-based responsibility, consumption-based and income-based responsibilities can also be applied to allocate global CO_2 emissions to certain countries. For a monitoring, we therefore suggest to determine all three types of responsibility, because reducing production-based CO_2 emissions does not necessarily imply reducing CO_2 emissions accounted with other metrics, and visa-verse. For example, taking into account only one perspective, such as the production-based responsibility, may neglect displacements of emission intensive technologies to other countries. The different perspectives can also bring light in terms of forest land use. These allow discussing resource use and pollution in terms of global responsibility and equity (Banuri et al., 2001). In this regard, it should be mentioned that, by using the environmentally extended data of EXIOBASE, several further emissions and resources can be determined in the same manner.

4. Discussion

4.1. Key findings

By disaggregating the corresponding industries in the EXIOBASE model, we conducted a detailed analysis of the German wood-based economy while taking into account the linkages to the other economies of the world. Such detailed analysis allowed a differentiated understanding of environmental and socio-economic impacts of the German wood use in 2007. The results of this study have shown that the combination of a global MRIO model with an increased level of detail in terms of bio-based product flows, which is achieved by disaggregation, complements one another and allows addressing six out of the eight goals of the German bioeconomy strategy: *change to bio-based economy*, *long term security of renewables*, *climate protection*, *innovation and competitiveness*, *jobs and value added* and *sustainable consumption*. The strength of applying a MRIO model compared to a mono-regional model results when addressing goals where different responsibilities for global emissions or resource consumption are taken into account: *long term security of renewables* and *sustainable consumption*. Besides the increase of reliability of input-output multipliers, the advantage of disaggregation is clearly demonstrated when goals are addressed for which an increased level of detail is needed: *change to bio-based economy*, *long term security of renewables*, *innovation and competitiveness*, *jobs and value added*.

Various indicators can be determined within the multi-regional input-output framework. As already mentioned, we do not claim to have achieved a complete list of indicators. Several further indicators can be determined using IO analysis: e.g., the comparison between the shares of fossil and non-fossil resources or resource related productivity measures (DESTATIS, 2014). We believe, however, that the illustrated analysis of wood use demonstrates the

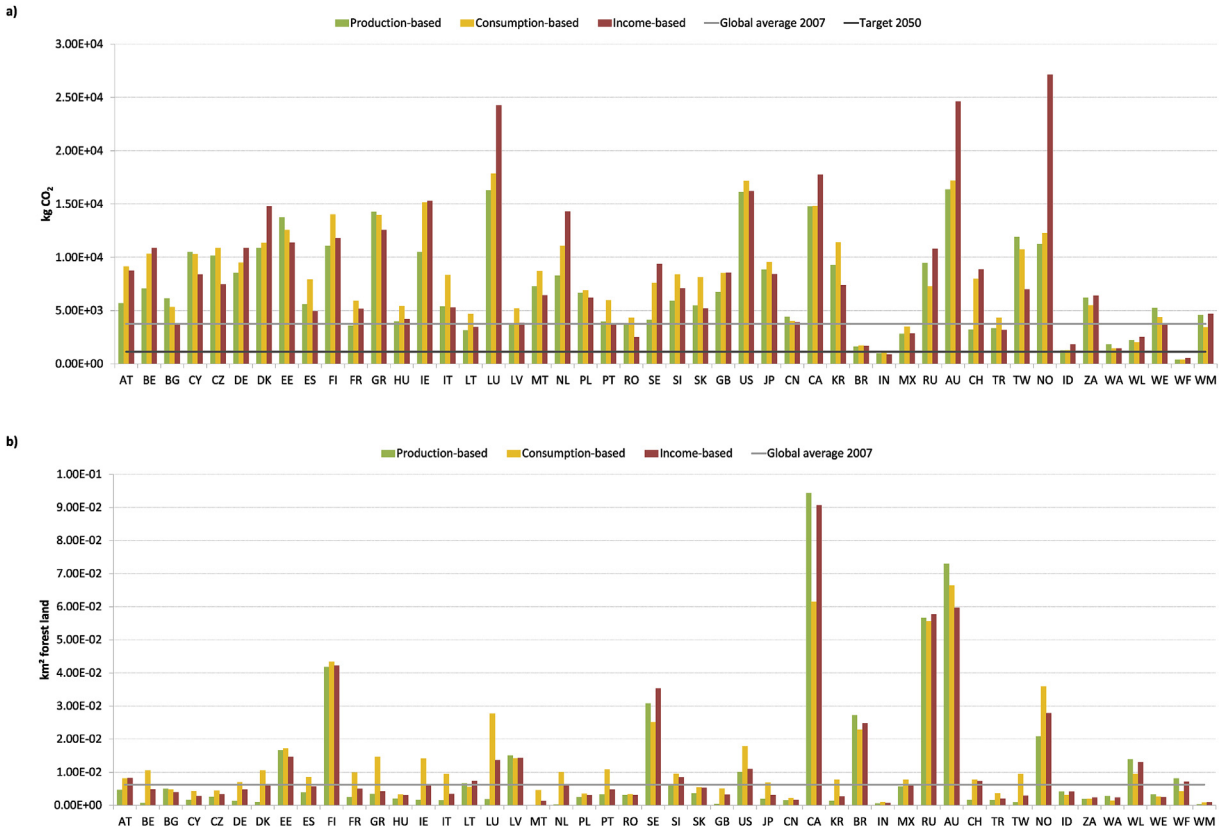


Fig. 3. Per capita CO_2 emissions and forest land use in 2007 - production-based, consumption-based and income-based responsibilities.

potential of MRIO models to address important societal challenges in a globalized world. The major challenge of climate change mitigation is "to ensure that neither the impact of climate change nor that of mitigation policies exacerbates existing inequities both within and across nations" (Banuri et al., 2001). This is true for all sustainability strategies that include other impacts in addition to those on climate change. Currently there is an ongoing discussion on reference values for environmental footprints (e.g., Steffen et al., 2015). For calculating CO_2 emissions, we defined a target value per capita according to van Vuuren et al. (2011) and de Koning et al. (2016) staying within the 2 °C target. An overview on the discussion about target values for other footprint indicators, such as water and material use per capita, is given by O'Brien et al. (2017) and Tukker et al. (2016). On the other hand, for goals that are restricted to national economies, such as *change to a bio-based economy* and *strengthening of innovation and competitiveness*, the quantification of target values is much more complex. In this work, we do not have the aim to finalize the discussion on target values. Instead, we argue that the formulation of national goals must be in line with ecological planetary boundaries. We argue that the transition towards bioeconomy, hence, can only be assessed taking into account global interdependencies; and that, according to the results obtained in this work, MRIO is an appropriate tool to adopt this global perspective.

4.2. Limitations and outlook

The disaggregation of industries is a non-trivial issue and builds the basis for several determined indicators. A major point of consideration is the simplified allocation of exported and imported forestry products of Germany according to production ratios. This neglects the fact that different types of forestry products do have different foreign trade balances (Seintsch, 2011). By using detailed information for all countries, however, type-specific trade flows of forestry products throughout the economies could be considered. A more straightforward approach would be to prevent the disaggregation by using even more detailed MRIO tables. To our knowledge, however, no MRIO database currently provides a more detailed wood-based product classification as provided in this study.

To monitor the changes towards a bioeconomy, it is necessary to carry out analyses including newer datasets. Additional research should also concern with enhancements to other types of biomass. Nonetheless, it is important to mention that the reason for considering the year 2007 in this work was the lack of updated data. Even though, a new version of the EXIOBASE database, which will provide time series for the period 1999–2011, has been announced (Wood et al., 2015). The general statements in this study are not affected by this fact. On the contrary, the unavailability of current and detailed information stresses the need for undertaking the ongoing effort of providing those comprehensive databases to finally get a holistic as well as a detailed picture for all sectors of the bioeconomy.

Limitations also exist in addressing the goals *secure supply of food* and *conserving biodiversity and soil fertility*. A recent study of Verones et al. (2017) has been tried to bridge the missing link between MRIO-based footprints and impacts on ecosystems. An example that determines species threatened by international trade using MRIO analysis is provided by Lenzen et al. (2012). For a monitoring of the bioeconomy, hence, further efforts should be done to implement methodologies that explicitly address impacts on biodiversity and to include food data. To address the goal *conservation of soil fertility*, additional monitoring approaches are

necessary that allow well-founded statements about the transition towards a sustainable bioeconomy (Juerges and Hansjürgens, 2016).

Another promising strategy to achieve a systemic monitoring, e.g., including the impacts on climate change due to land use change, would be the linking to different models (e.g., Schaldach et al., 2011) within an integrated assessment framework (O'Brien et al., 2017; Pauliuk et al., 2017). The combination of research communities studying human and natural earth systems will become increasingly important for the understanding of nonlinear and interactive systems. An option to increase the understanding of carbon storage in products during its life cycle would be the analysis with dynamic models (Pauliuk et al., 2014). These ex-ante modeling approaches could help to not only study future pathways towards sustainability, but also to provide better advice to policy-makers. Thereby, the consideration of the various options of biomass utilizations as food, feed, materials, chemicals and energy would be a significant step towards a responsible bioeconomy (cf., Ingrao et al., 2016).

5. Conclusion

MRIO analysis has proven to be a powerful tool that is well-suited for the ex-post monitoring of the progress towards a bioeconomy. It provides an overall consistency and allows the assessment of various political and societal goals. The proposed indicators can be a basis for further discussions on the definition of target values and the creation of a comprehensive bioeconomy monitoring that controls target achievement and identifies trade-offs. To overcome current limitations, efforts of data collection and synchronization as well as studies, in which more current data will be used, are necessary. To address all goals of the bioeconomy strategy, additional efforts and support by other approaches are necessary. The inclusion of further types of biomass within a systemic monitoring would significantly increase the understanding of the complex system bioeconomy and allow the design of precautionary instruments for its governance. Furthermore, we conclude that this work contributes to take on the global perspective in the field of developing sustainable bio-based production and energy generation technologies.

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