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Effective bioeconomy? a MRIO-based socioeconomic and environmental impact assessment of generic sectoral innovations

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ABSTRACT

The European Commission (EC) expects a bioeconomic transition to have both environmental and socioeconomic benefits. While bioeconomic impact assessments exist, they usually focus on a particular sustainability dimension and on specific products or technologies. To draw a more holistic picture, this paper aims to analyze the substitution impacts of four bioeconomic innovations in terms of policy objectives as formulated by the EC. We estimated the indirect impacts resulting from a partial replacement of non-bio-based inputs with bio-based substitutes in the transport equipment, construction, textile, and chemical sectors. A multi-regional input-output (MRIO)-based approach was used to yield point estimates and uncertainty intervals. While our results point to a number of possible socioeconomic and environmental benefits, there is an astonishing diversity of outcomes across the scenarios with regard to their potentials and limitations to contribute to policy objectives. Decisions on future utilization paths of biomass will strongly influence the characteristics of an upcoming bioeconomy in terms of sustainability. Mere promotion of additional biomass use as a policy strategy is not sufficient to pursue the development of an effective bioeconomy capable to deliver "sustainable growth."

1. Introduction

The term bioeconomy is increasingly being used in science (Bugge et al., 2016) and policy (Pahun et al., 2018). Apart from its inclusion in many national policies (El-Chichakli et al., 2016), international organizations such as the OECD (OECD, 2009) or the EU (Levidow et al., 2013; European Commission, 2018) refer to *the bioeconomy* as a political vision. The term may be interpreted in several ways (Levidow et al., 2013; Bugge et al., 2016), e.g. focusing on bio-technology (OECD), bio-resources (EU) (Levidow et al., 2013; Staffas et al., 2013), or biorefineries (e.g. the International Energy Agency) as an underlying techno-economic concept. These concepts are closely related to various research and innovation policies and to the growing need for international cooperation (Levidow et al., 2013; Schütte, 2018).

The European Commission (EC) expects a bioeconomic transition to reduce GHG emissions, increase resource and land-use efficiency, create new business opportunities, support EU global market leadership, and to provide an economic and employment stimulus to rural and regional development (Imbert et al., 2017). In more detail, the update of the EU bioeconomy strategy (European Commission, 2018) refers to concrete objectives including ensuring food and nutrition security, managing natural resources sustainably, reducing dependence on non-renewable, unsustainable resources whether sourced domestically or from abroad, mitigating and adapting to climate change, and strengthening European competitiveness and creating jobs.

The attempt to fulfill such a diversity of objectives by promoting bioeconomies entails a host of competing goals (Boehlje and Bröring, 2011). The trade-offs existing across the three dimensions of sustainability (economic, social and environmental), are reflected, for example, in the food-fuel debate (Rathmann et al., 2010) or in the discussions surrounding wood use for energy vs. material applications (Schwarzbauer and Stern, 2010). In addition, Richardson (2012) highlighted the existence of three axes contesting the dominant narrative of a bioeconomy. First, the extent to which rural communities (in Europe or elsewhere) would benefit from the extension of bio-based commodity chains is disputed. Second, the potential environmental impacts of a bioeconomy are subject to discussion. Assuming that a bioeconomy aims at changing the material content of products and fuels towards renewable materials, it has been questioned, for example, how

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or whether this may make a significant contribution to the reduction of GHG emissions (Richardson, 2012). Third, civil society expressed concern about problems associated with bioeconomy, such as land grabbing or deforestation (Richardson, 2012). Both the competing goals dilemma and the contested bioeconomy narrative demonstrate the need for research into bioeconomy.

Studies on impact assessment or transition processes related to bioeconomy tend mostly to analyze particular sustainability dimensions and specific products or technologies, such as biofuels, biotechnology or biorefineries, often within specific geographic contexts. Bracco et al. (2018) for example reviewed the contribution of bioeconomy to national economies. The economic impacts arising from the conversion of pulp mills into biorefineries are assessed by Stern et al. (2015). Egenolf and Bringezu (2019) provide a conceptualization of indicators for the sustainability assessment of the bioeconomy, while van Schoubroeck et al. (2018) investigated sustainability indicators with respect to bio-based chemicals. Potential social impacts of introducing biofuel technologies are assessed using the Delphi method (Ribeiro and Quintanilla, 2015). Economic impacts pertaining to different diffusion paths of biotechnology are analyzed by Wydra (2011) by combining technology information and scenario assumptions in input-output models. The results showed that the impact on production and employment differs greatly between sectors, with the indirect economic effects of biotechnology exceeding the direct economic effects. Loizou et al. (2019) apply input-output modeling to assess the potential for a bioeconomy in Poland. Changing expectations with respect to biomass as a resource base were investigated by Kirkels (2016). Pitkänen et al. (2016) provide a qualitative, descriptive, multiple case study of bioecomic innovations at different levels, addressing learning effects. Hurmekoski et al. (2018b) apply a backcasting methodology in order to focus on potential pathways in the area of wood-based buildings. Maes and van Passel (2019) investigate bioeconomic innovation policies under a biomass resource constraint. Based on expert workshops Tegart (2009) discusses various options for future energy demands, several of them relating to bioeconomy.

The inherent conflict and controversy surrounding the notion of a bioeconomy clearly call for a holistic approach when attempting to assess the potential impacts of relevant innovations. Such a holistic assessment requires the consideration of trade-offs between socioeconomic and environmental dimensions. Furthermore, the existence of material and financial constraints requires that comparative assessments be made in order to provide a suitable information base for decision makers. The present paper thus aims at analyzing the potential substitution impacts of four bioeconomic, generic innovations in terms of policy objectives formulated by the European Commission (2018). More precisely, the research goal is to assess the net socioeconomic and environmental effects when a share of non-bio-based inputs is replaced by bio-based substitutes in the transport equipment, construction, textile, and chemical sectors.

In the following subsections we describe the current state of the sectors studied in terms of innovative uses of biomass (0). Then, scenarios are introduced under which the sectors extend their bio-based inputs on the expense of conventional ones (0). Next, the details on the estimation of the associated substitution effects and underlying data are specified (0, 0). In the results section, we present estimated substitution-induced changes for each of the indicators considered (0). Finally, several characteristics of the innovation cases are discussed with regard to their potential and limitations to contribute to policy objectives (0, 0, 0), and the assumptions and limitations of the approach are summarized (0). We conclude by sketching some implications of the findings for policy (0).

2. Methodology

A variety of approaches are used in the relevant literature in order to analyze and model economy-wide material and energy flows. In principle, high-resolution life cycle inventory (LCI) data could be aggregated to arrive at economy-wide flows of material and energy inputs, waste and emissions. However, ensuring full coverage of products considered while avoiding double counting of underlying flows during the aggregation process is both time-consuming and error-prone (Schaffartzik et al., 2014). In multi-regional input-output (MRIO) analysis, due to its top-down nature, the impact of such aggregation issues is much less relevant. Geographical representation is implemented in more detail in MRIO compared to LCI approaches, although methods for improving LCI regionalization are currently gaining in importance (Yang, 2016). On the other hand, MRIO operates at a significantly lower sectoral resolution, which is a possible additional source of uncertainty (Steen-Olsen et al., 2014). Given that the aim of the present study is to assess economy-wide substitution impacts while also taking account of related regional aspects, we opted for an MRIO-based approach. The approach employs ceteris paribus simulations of four scenarios, in which the European transport equipment, construction, textile, and chemical sectors introduce or extend a bio-based generic innovation. Each innovation is modelled as an input substitution, where some of the conventional inputs are replaced by bio-based ones. Thus, the substituting sectors undergo technological change, while the rest of the economic structure (technologies, products, size distribution of enterprises, international competitiveness, etc.) is held constant to isolate the substitution effects on key indicators for bioeconomy development (Table 1). The simulations are performed for each year within the period from 1995 to 2009 in order to reveal how changing economic conditions affect the estimated substitution effects. In addition, the approach uses Monte Carlo simulation to assess uncertainty. In the next section we provide more detail on real-world bio-based substitution in the four sectors analyzed.

2.1. Sectors

2.1.1. Transport equipment sector

The automotive industry faces growing pressure to reduce the GHG emissions of its fleet (European Commission, 2014) and to simultaneously increase the recyclability of its components (European Commission, 2000). A reduction in vehicle weight and in

Table. 1
Mapping bioeconomy objectives with socioeconomic and environmental indicators based on European Commission (2018), Egenolf and Bringezu (2019), and O'Brien et al. (2017).

Bioeconomy objective	**Indicator**
strengthening European competitiveness and creating jobs	+ changes in labor compensation + changes in persons engaged + changes in hours worked + changes in capital compensation
reducing dependence on non-renewable resources, mitigating and adapting to climate change	– changes in fossil and mineral resource use – changes in emissions to air
managing natural resources sustainably and ensuring food and nutrition security	– changes in biomass use – changes in land use – changes in water use

Table. 2
Range of potentially affected sub-sectoral activities of wood-based substitution occurrences in the transport equipment sector (34–35). Activities are classified according to the PRODCOM List 2006 (Eurostat, 2006).

Replaced inputs – basic metals and fabricated metal (27–28)	
27.10	Manufacture of basic iron and steel and of ferro-alloys
27.22	Manufacture of steel tubes
27.31	Cold drawing
27.33	Cold forming or folding
27.41	Precious metals production
27.42	aluminum production
27.43	Lead, zinc and tin production
27.45	Other non-ferrous metal production
27.75	Manufacture of other fabricated metal products n.e.c.
28.11	Manufacture of metal structures and parts of structures
28.40	Forging, pressing, stamping, and roll forming of metal; powder metallurgy
28.51	Treatment and Coating of metals
28.52	General mechanical engineering
Replacing inputs – wood and products of wood and cork (20)	
20.10	Sawmilling and planing of wood; impregnation of wood
20.20	Manufacture of veneer sheets; manufacture of plywood, laminboard, particle board, fiber board and other panels and boards
20.51	Manufacture of other products of wood

fuel consumption is needed in order to meet the emission targets. One strategy for reducing weight is to replace steel with lighter materials such as aluminum, high strength steel, magnesium, or glass or carbon fiber composites (Mayyas et al., 2012). Bio-based materials have mostly been implemented in the form of reinforcements for polymer matrices, e.g. in place of glass or carbon fibers in structural and non-structural components (AL-Oqla and Sapuan, 2014; Boland et al., 2016). Although composites with natural reinforcements may be beneficial in terms of integrating renewable materials, they are not sufficiently eco-friendly due to their petroleum-based source and to the non-biodegradable nature of the polymer matrix (Mohanty et al., 2002). Apart from such bio-based composite solutions, steel components in vehicles may in some cases be replaced by wood-based multi-material systems. The weight reduction potential of such a substitution amounts to 15–20% (Kohl et al., 2016). The possibility of implementing wood in automotive applications is still being researched in several projects (Leitgeb et al., 2016). The sub-sectoral activities that may be affected by wood-based substitution in automotive applications are summarized in Table 2.

Table. 3
Range of potentially affected sub-sectoral activities of wood-based substitution occurrences in the construction sector (F). Activities are classified according to the PRODCOM List 2006 (Eurostat, 2006).

Replaced inputs – other non-metallic mineral (26); basic metals and fabricated metal (27–28)	
26.30	Manufacture of ceramic tiles and flags
26.40	Manufacture of bricks, tiles and construction products, in baked clay
26.51	Manufacture of cement
26.52	Manufacture of lime
26.53	Manufacture of plaster
26.61	Manufacture of concrete products for construction purposes
26.62	Manufacture of plaster products for construction purposes
26.63	Manufacture of ready-mixed concrete
26.64	Manufacture of mortars
26.65	Manufacture of fiber cement
26.66	Manufacture of other articles of concrete, plaster and cement
26.70	Cutting, shaping and finishing of ornamental and building stone
27.10	Manufacture of basic iron and steel and of ferro-alloys
27.32	Cold rolling of narrow strip
27.33	Cold forming or folding
27.42	aluminum production
27.43	Lead, zinc and tin production
27.44	Copper production
28.11	Manufacture of metal structures and parts of structures
28.12	Manufacture of builders' carpentry and joinery of metal
28.40	Forging, pressing, stamping and roll forming of metal; powder metallurgy
28.51	Treatment and coating of metals
28.75	Manufacture of other fabricated metal products n.e.c.
Replacing inputs – wood and products of wood and cork (20)	
20.10	Sawmilling and planing of wood; impregnation of wood
20.20	Manufacture of veneer sheets; manufacture of plywood, laminboard, particle board, fiber board and other panels and boards
20.30	Manufacture of builders' carpentry and joinery

2.1.2. *Construction sector*

When looking at the whole lifecycle of buildings, 42% and 30%, respectively, of the total energy and water consumed in Europe, may be attributed to the construction sector. The latter is also responsible for the use of 50% of extracted materials, and emits some 35% of anthropogenic GHG emissions (European Commission, 2011). Buildings are always made of a combination of different materials such as concrete, aggregate materials (sand, gravel and crushed stone) and steel, with wood accounting for less than 2% of total material used in the European construction sector (Herczeg et al., 2014). Studies showed that wood-based construction products have, on average, a lower carbon footprint compared to their fossil-based counterparts such as concrete, steel and aluminum-based products (Leskinen et al., 2018). The replacement of high carbon products with wood-based ones is thus considered part of the portfolio of actions that can help to limit global warming (IPCC, 2018) and a generalized increased use of wood in construction is seen as an important avenue towards sustainable development, both in the EU (European Commission, 2012), and in other countries around the world (Goodland, 2016). Construction represents, for the wood industries, the largest value-added markets, particularly since wood is traditionally used to build single-family homes (UNECE, 2019). Although concrete and steel dominate non-residential construction (UNECE, 2019), the development in the last decades of engineered wood products (EWP) such as cross-laminated timber (CLT), I-beams (also called I-joists), laminated veneer lumber (LVL) and glued laminated timber (glulam), together with the move in the direction of industrial prefabrication and standardization of wood-based components, has made the use of wood in multi-story and industrial buildings more competitive. The positive public perception of wood use in construction, related advances in technology (Manja Kitek Kuzman et al., 2018), together with stricter environmental regulations in the building sector[1] all facilitate the substitution of fossil-based materials with wood. The sub-sectoral activities that may be affected by wood-based substitution in the construction sector are summarized in Table 3.

2.1.3. *Textile sector*

Production in the textile industry is highly globalized and decentralized and plays a major role in the global economy (Muthu, 2014; Strähle and Müller, 2017). In 2016, the global consumption of textiles was around 100 × 10^6 t for the first time and an annual growth rate of 3% was predicted up to 2020 (The Fiber Year Consulting, 2017). Due to high consumption and the wide range of applications for textiles, the sector has a major environmental impact (Muthu, 2014). A large part of these effects arises at the beginning of the value chain, i.e. in fiber production. Of the fibers consumed worldwide, synthetic polymers from fossil-based resources, such as polyester and polyamide, made up 62.5% of the total in 2018. Cotton dominates by far among those fibers made from natural polymers (Lenzing Group, 2019). Although cotton fibers are made from renewable raw material, their production entails considerable environmental impact in terms of water consumption, land use and the use of pesticides (Ütebay et al., 2019). It is therefore essential that alternatives to fossil-based fibers and cotton be found. Wood-based cellulose fibers, especially from the lyocell process, can

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[1] See e.g. the voluntary EU level(s) framework (http://ec.europa.eu/environment/eussd/buildings.htm).

Table. 4
Range of potentially affected sub-sectoral activities of wood-based substitution occurrences in the chemicals and chemical products sector (24). Activities are classified according to the "Statistical Classification of Products by Activity in the European Economic Community, 2002 version" (Eurostat, 2002) and to the PRODCOM List 2006 (Eurostat, 2006).

Replaced inputs – coke, refined petroleum and nuclear fuel (23)	
23.10	Coke oven products
23.20	Refined petroleum products
Replacing inputs – pulp, paper, printing and publishing (21–22)	
21.11	Manufacture of pulp

make a valuable contribution in this regard (Sayyed et al., 2019). For many applications, the properties of such fibers mean that they have the potential to compete with synthetic fibers and cotton (Sayyed et al., 2019). In 2018, wood-based cellulose fibers such as lyocell, viscose and modal, already accounted for 6.3% of global fiber consumption (Lenzing Group, 2019). The sub-sectoral activities that may be affected by wood-based substitution in the chemical sector are summarized in Table 4. In contrast to the other scenarios, the range of sub-sectoral flows potentially used as substitutes is limited and covers only part of the total sector. Thus, the use of the input structure of the total sector as a representation of the substitutes' inputs may lead to distorted results. To counteract this, we carried out a volume calibration for the textile scenario. As pulp has a higher volume per value unit ratio than the total output of the sector (Eurostat, 2018), we increased the substitution value for the substitute accordingly (1.87). With respect to the initial substitution value, this resulted in a volume-value ratio of the total sector corresponding to that of pulp, and thus improves accuracy when estimating the environmental effects associated with pulp use as a substitute. The socioeconomic indicators were assumed to be more closely correlated with value rather than with volume and thus not subject to volume calibration.

2.1.4. Chemical sector (residue use)

Energy carriers, as well as products such as polymers and chemicals, are to a large extent based on fossil resources, and thus contribute to problems such as high GHG emissions (Greene et al., 2006; van Heiningen, 2006; De Jong et al., 2012). An estimated 16% of fossil-based oil products is used for non-energy applications. This includes the petrochemical products themselves, as well as the energy required to produce them (De Jong et al., 2012). Several factors work to hinder the development of bio-based chemicals, i.e. the relatively low price of crude oil, the ready availability of fossil-based chemicals, the difficulty in finding functional equivalents which are both economically feasible and more sustainable, and the inherent complexity of the chemicals segment (Bozell, 2008; De Jong et al., 2012). Thus, in the European Union, only an estimated 3% of the chemical products are based on biogenic feedstock (Spekreijse et al., 2019). However, prevailing drivers such as volatile oil prices, insecure supply, and consumer demand for more environmentally friendly products could lead to the production of more bio-based and even bulk chemicals in the future (Bozell, 2008; De Jong et al., 2012; Spekreijse et al., 2019). Several political actions, such as research funding programs, have now been initiated in this direction (e.g., Spekreijse et al., 2019). The US Department of Energy has issued reports on the development of building blocks for chemicals from sugars and synthesis gas (Werpy et al., 2004; Bozell and Petersen, 2010), and lignin (Holladay et al., 2007). The latter, lignin, is regarded as a promising compound (underutilized side-stream, main bio-based aromatic resource, wide variety of products conceivable) and expected to play major roles in biorefinery conception (Stewart, 2008; Ragauskas et al., 2014; Isikgor and Becer, 2015). Currently, wood-pulping processes are usually focused and optimized with respect to cellulose production (Michels and Wagemann, 2010). Lignin is largely (about 98%) burnt on site for the purposes of recovering the process chemicals and of gaining energy, covering the energy demands of the chemical pulp mills and providing a surplus (Isikgor and Becer, 2015). Improvements in energy efficiency in pulp mills could enable value-added products to be produced from a part of the generated technical lignin without affecting the required energy supply (van Heiningen, 2006; Holladay et al., 2007). Despite major efforts, still only 2% of the estimated 50×10^6 t of technical lignin available worldwide are isolated from spent pulping liquors and used commercially in rather limited markets (Gargulak and Lebo, 1999; Lora and Glasser, 2002; Saake and Lehnen, 2012; Isikgor and Becer, 2015). The sub-sectoral activities that may be affected by residue-based substitution in the chemical sector are summarized in Table 5.

2.2. Scenarios

In each of the four substitution scenarios (summarized in Table 6) an identical pattern is followed in which the European (EU-27) *substituting sectors* replace a *fraction* of specific conventional inputs (*replaced inputs*) in monetary terms by the same monetary value of bio-based substitutes (*replacing inputs)*. The fraction of replaced inputs corresponds to a *value* of 10^9 USD (2009) in all scenarios. This value is an arbitrary parameter and does not represent a maximum achievable potential. It was kept constant for all scenarios to facilitate the comparison of results. For example, under the vehicle scenario, the European transport equipment sector replaces 0.93% of its basic metal and fabricated metal inputs worth 10^9 USD, by wood and products of wood and cork worth 10^9 USD. The rationale behind the monetary identity of replaced inputs and replacing inputs is that an applicable substitute is at least equivalent in terms of function and cost. We therefore assume the availability of cost-neutral substitutes for each scenario. Concerning the countries of origin of replaced and replacing inputs, the initial composition is retained, i.e. origin proportions before and after substitution are equal and the substitution draws on existing trade relations. To meet the different conditions of the innovations investigated, we differentiated two *types* of replacing inputs, namely products (sometimes also called determining products or reference products) and residues (sometimes referred to as near-waste or not fully utilized by-products) (Consequential-LCA, 2015b; Consequential-LCA, 2015a). Pulp and technical lignin are examples of process outputs, the former being a product, and the latter a residue. For the current assessment the relevant difference between products and residues is that a change in demand for a product affects upstream supply chains, whereas this is

Table. 5
Range of potentially affected sub-sectoral activities of residue-based substitution occurrences in the chemicals and chemical products sector (24). Activities are classified according to the "Statistical Classification of Products by Activity in the European Economic Community, 2002 version" (Eurostat, 2002).

Replaced inputs – coke, refined petroleum and nuclear fuel (23)	
23.10	Coke oven products
23.20	Refined petroleum products
Replacing inputs – exploitation of unused capacities	
	Wood-based technical lignin is a side-stream derived from chemical pulping processes, which are primarily aimed at the production of pulp (sub-sector 21.11) for an array of different products such as paper. Technical lignin is currently for the most part burned on-site for the purposes of recovering the process chemicals and of generating energy (Isikgor and Becer, 2015).

Table. 6
Substitution scenario assumptions. Sectors are classified according to the WIOD release 2013 based on the International Standard Industrial Classification Rev. 3. *Fraction* denotes the share of conventional inputs to be substituted. Volume calibration refers to an adjustment of the volume of replacing inputs.

Scenario name	Vehicle	Construction	Textile	Chemical
Substituting sectors	Transport equipment (34–35)	Construction (F)	Chemicals and Chemical Products (24)	Chemicals and Chemical Products (24)
Replaced inputs	Basic metals and fabricated metal (27–28)	Other Non-Metallic Mineral (26); Basic metals and fabricated metal (27–28)	Coke, Refined Petroleum and Nuclear Fuel (23)	Coke, Refined Petroleum and Nuclear Fuel (23)
Fraction	0.93%	0.42%	3.56%	3.56%
Value	10^9 USD (2009)	10^9 USD (2009)	10^9 USD (2009)	10^9 USD (2009)
Replacing inputs	Wood and products of wood and cork (20)	Wood and products of wood and cork (20)	Pulp, Paper, Printing and Publishing (21–22)	Exploitation of unused capacities[1]
Value	10^9 USD (2009)	10^9 USD (2009)	10^9 USD (2009)	–
Volume calibration	1	1	1.87	–
Type	Products	Products	Products	Residues

[1] Value is added to the substitution value balance of Pulp, Paper, Printing and Publishing (21–22) industry that supplies lignin (assumed to be a previously unused residue) to the substituting sectors.

not the case for (previously unused) residues. Finally, the application of a *volume calibration* was necessary in the textile scenario (see 0 for details).

2.3. Model

To estimate the cumulative (direct and indirect) substitution impacts on the indicators in focus (Table 1), we used a multi-regional input-output (MRIO)-based approach. We started from the basic MRIO model (Miller and Blair, 2009) that allocates total outputs of the sectors to final consumption via the Leontief inverse $(\mathbf{I}-\mathbf{A})^{-1}$ as shown in Eq. (1)

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

where $\mathbf{x}$ is the mn-by-1 total output vector of the n sectors in m countries, $\mathbf{I}$ is an mn-by-mn identity matrix, $\mathbf{A} = \mathbf{Z}\ \mathrm{diag}(\mathbf{x})^{-1}$ is the mn-by-mn input coefficient matrix, $\mathbf{y} = \mathbf{Y}\iota$ is the mn-by-1 final consumption vector that shows the aggregated final consumption of the n sectoral outputs produced in m countries; $\mathbf{Y}$ is the mn-by-mo final consumption matrix differentiating o consumption classes (e.g. household and government expenditures), and ι an mo-by-1 vector of ones. $\mathbf{Z}$ symbolizes an mn-by-mn matrix representing all inter-industry flows in monetary terms.

$$\mathbf{x}' = (\mathbf{I}-\mathbf{A}\odot\mathbf{S})^{-1}\mathbf{y} \tag{2}$$

We created an mn-by-mn matrix $\mathbf{S}$ encompassing the substitution coefficients according to the scenario description and altered the input coefficient matrix $\mathbf{A}$ ($\odot$ denotes the Hadamard product). Substitution is assumed to increase or decrease the outputs of the affected sectors as a whole while final consumption remains constant. With unaffected final consumption $\mathbf{y}$ and an identity matrix $\mathbf{I}$, a new mn-by-1 vector $\mathbf{x}'$ was calculated that depicts the total outputs of the n sectors in m countries after the substitution, including direct and indirect substitution impacts (Eq. (2)).

$$\mathbf{c} = \mathrm{diag}(\mathbf{x})^{-1}\mathbf{x}' \tag{3}$$

$$\Delta\mathbf{E} = \mathbf{E}\mathrm{diag}(\mathbf{c}) - \mathbf{E} \tag{4}$$

Subsequently, $\mathbf{x}'$ was normalized by $\mathbf{x}$, yielding the mn-by-1 output change vector $\mathbf{c}$ (Eq. (3)). This vector represents the output change coefficients caused by the substitution scenario. Output changes were assumed to linearly impact the p indicators in focus – for example, a 1% increase in output production of a given sector and country is associated with a 1% increase in direct emissions to air of that sector. As shown in Eq. (4), substitution impacts on indicators are presented in absolute terms ($\Delta\mathbf{E}$), where the p-by-mn extension matrix $\mathbf{E}$ captures data on the p indicators that are directly associated with the production of output in the n sectors in m countries.

MRIO analyses exhibit two essential sources of uncertainty – the assumptions of a homogenous composition and a homogenous price across all output supplies of a given sector. To which extent these assumptions hold empirically is difficult to show as the sectoral resolution r requires r^2 data points in the inter-industry-matrix. This rapidly increases the data requirements to orders of magnitude that can no longer be compiled with justifiable effort. Other strategies to assess data reliability are therefore necessary. We addressed this question in the present study by making use of intertemporal variation in MRIO data in order to present the range of variation in results. This gives an impression of the robustness of results in an ever-changing environment, i.e. one subject to varying composition in terms of prices and sectoral flows. We also conducted Monte Carlo simulations, calculating the substitution impacts at the level of randomly disaggregated sectors, in order to obtain result intervals at the aggregated level. To perform Monte Carlo simulations, we disaggregated each sector into two new sectors. This led to a doubling of rows and columns and, to preserve the initial mn-by-mn dimensions, to $d = 2^2$ new matrices $\mathbf{Z}^{(1)}, \ldots, \mathbf{Z}^{(d)}$. To populate these matrices, we allocated the initial inputs and outputs using random matrices $\mathbf{R}^{(1)}, \ldots, \mathbf{R}^{(d)}$ of the same dimension sampled from a uniform distribution $U(0, 1)$.

$$\mathbf{Z}^{(i)} = \mathbf{Z}\odot\mathbf{R}^{(i)}\oslash\sum_{j=1}^{d}\mathbf{R}^{(j)} \tag{5}$$

Eq. (5) creates disaggregation solutions for $\mathbf{Z}$. $\mathbf{E}$ and $\mathbf{y}$ are disaggregated analogously. With $\mathbf{Z}^{(i)}$, $\mathbf{E}^{(i)}$, and $\mathbf{y}^{(i)}$, Eq. 4 was used to yield p-by-mn disaggregated substitution impact matrices $\Delta\mathbf{E}^{(i)}$ ($\odot$ denotes the Hadamard product, $\oslash$ the Hadamard division). Upon re-aggregation we obtained a Monte Carlo-perturbed substitution impacts matrix $\Delta\mathbf{E} = \sum_{i=1}^{d}\Delta\mathbf{E}^{(i)}$. The procedure was repeated 10^3 times in order to achieve satisfactory stabilization of result distribution. This approach shows how widely the substitution impact estimates, based on simulated disaggregation, are spread around the initial point estimate under the specified conditions. The Monte Carlo simulation only includes a subset of all possible outcomes as sectoral disaggregation patterns leading to extreme results occur with lower frequency, when randomly generated, and are thus possibly not represented in the result intervals.

2.4. Data

From the several multi-region input-output (MRIO) databases currently available, we selected the World Input-Output Database release 2013 (WIOD) (Timmer et al., 2015) for use. Compared to other MRIO data sources such as EORA, GTAP, or EXIOBASE, WIOD exhibits several properties which help us meet our objective. First, at the time the analysis was performed, WIOD and EORA were the only databases

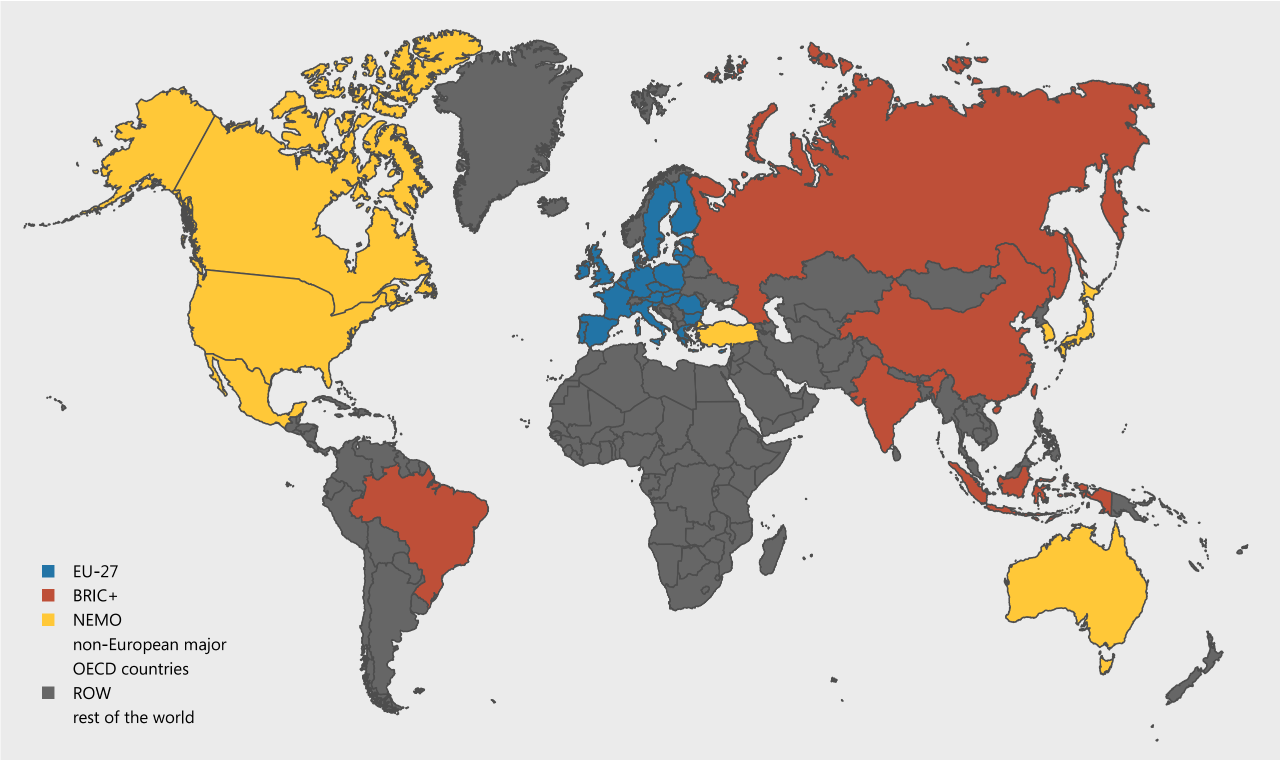

Fig. 1. Regional aggregates for result presentation; Blue: EU-27 (EU-27 member countries), Red: BRIC+ (Brazil, China, Indonesia, India, Russia, Taiwan), Yellow: NEMO (non-European major OECD countries [Australia, Canada, Japan, South Korea, Mexico, Turkey, USA]; gray: ROW (rest of the world).

providing publicly available annual time series data (Mattila, 2018). Second, of these two, WIOD incorporates labor and capital compensation as socioeconomic extensions. This information was not available in EORA according to their list of indicators (KGM, 2018). Furthermore, WIOD covers a number of environmental indicators such as biomass use, and GHG emissions that closely relate to key bioeconomy objectives (see Table 1). Third, WIOD is more transparent regarding data sources and compilation principles, including those relating to socioeconomic and environmental accounts. On the other hand, our selection also entailed a few (in our view, minor) disadvantages. First, the time series of the release used ends in 2011. This, together with the data gaps in the socioeconomic accounts for the years 2010 and 2011, restricts usage of the database to no later than 2009. In order to address the question of temporal stability, the variations in substitution impacts over time are presented in the results section. Second, the level of sectoral aggregation employed in WIOD may be a source of inaccuracy. While the aggregation level (sectoral resolution) was found to have quite limited effects on economic indicators, a comparative analysis suggests that its impact on CO_2 emission footprints, and possibly on other environmental indicators, is likely to be larger (Steen-Olsen et al., 2014). To address this issue, we assessed the sensitivity of the results using Monte Carlo simulation.

WIOD provides comprehensive documentation on its socioeconomic and environmental extension data. We present here an overview of the data sources and uncertainties with regard to the indicators under study. In order to augment WIOD with labor data, the EU KLEMS database (release 2009) was used for most of the countries (O'Mahony and Timmer, 2009; Erumban et al., 2012). Sources of uncertainty arise here when disaggregating data from national labor force surveys into more finely-grained sectors, and when attempting to deal with country-specific deviations in the definitions of employment (persons or jobs vs. full-time equivalent) and hours worked (contractual vs. actual). Furthermore, data uncertainties exist regarding the number and income of self-employed persons (Timmer et al., 2007). Capital compensation is defined as gross value added minus labor compensation, meaning that the labor-related sources of uncertainty also apply here. In some cases, capital compensation is negative, which might be due to an overestimation of self-employed persons' incomes (Timmer et al., 2007). Material use extension data originates from an earlier version of the Global Material Flows Database (GMFD) (Genty et al., 2012; International Resource Panel, 2018), a meta-compilation of material flow data based on national and international statistical sources. Uncertainties related to material extraction data concern the estimation of grazed biomass via theoretical feed energy requirements, the correction measures used to avoid double-counting of crushed rock, and the derivation of ore extraction based on reported metal flow figures. Furthermore, as a result of data unavailability, items such as biomass harvest or removal from subsistence agriculture, home gardening, infrastructure areas, and set-aside agricultural land were ignored (Eurostat, 2007).

Emissions to air were estimated using NAMEA (national accounting matrices including environmental accounts)-air like data. Where necessary, data were drawn from national emission inventories or converted from energy use statistics provided by the International Energy Agency (IEA, 2019). The reported uncertainties concern deviations in the estimation methodologies of the various data sources (Genty et al., 2012). In the present study, emissions to air are presented as CO_2 equivalents using IPCC 100-year time horizon GWP factors (Myhre et al., 2014). Land use extension data was derived from FAOSTAT (FAO, 2017). The source reports total forest area and does not differentiate between economic and non-economic forest use (e.g. nature reserves). However, in the context of input-output analysis, only the forest area that is directly associated with forestry output production should be included in the accounts (Bruckner et al., 2015). The productive forest areas were therefore estimated by dividing the annual wood harvest by the area productivity quotients commonly stated in the relevant literature (reference year 2005) (Genty et al., 2012). With regard to water use, country- and type-specific water intensities by crop and livestock species were compiled from the literature and multiplied with annual crop production and livestock maintenance statistics from

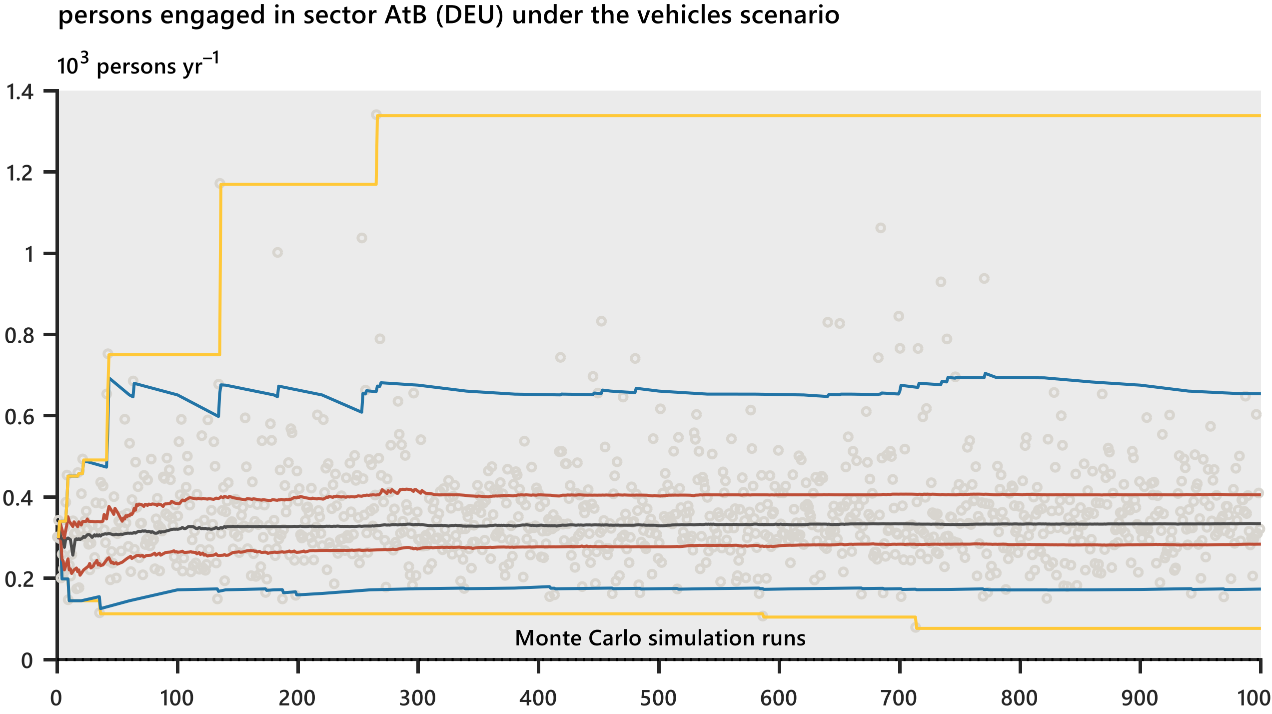

Fig. 2. Monte Carlo simulation runs (x-axis) and absolute changes in persons engaged (y-axis) using the example of the German (DEU) Agriculture, Hunting, Forestry and Fishing sector (AtB) under the vehicle scenario in 2009. The panel shows individual results of each run (light gray circles) and quantiles of the cumulated results up to the respective run ($p = 0.5 \pm 0.5$ [yellow lines]; $p = 0.5 \pm 0.475$ [blue lines]; $p = 0.5 \pm 0.25$ [red lines]; $p = 0.5$ [gray line]).

FAOSTAT. To estimate hydropower generation, a global average water intensity factor was applied. For other industrial production sectors estimations of total country- and type-specific water use were allocated to WIOD sectors on the basis of sectoral characteristics and sectoral outputs at constant prices (Genty et al., 2012).

3. Results

This section reveals the absolute changes in selected indicators under the four substitution scenarios. For clarity, we present the results aggregated for the four macro-regions shown in Fig. 1. For each indicator, three components are displayed, a) the point estimates of absolute changes due to substitution in 2009, b) the variation in estimates for each year of the period 1995–2009, and c) the estimated variation resulting from Monte Carlo simulation with data from 2009. For illustrative purposes, Fig. 2 provides results of a Monte Carlo simulation example at the sectoral level. Please note the gaps in the data with respect to labor indicators and capital compensation.[2]

3.1. Labor indicators

At 268 × 10^6 USD yr^{-1}, the textile scenario shows the largest cumulative labor compensation increases in EU-27, BRIC+, and NEMO (Fig. 3). The results for the vehicle and construction scenarios are also positive but clearly lower, at 25 × 10^6 USD yr^{-1} and 46 × 10^6 USD yr^{-1} respectively, while the chemical residue use scenario is the only one to show a negative change with –302 × 10^6 USD yr^{-1} (point estimates). Overall, the results are dominated by the changes in the EU-27, with negative effects in BRIC+ playing a role in the textile and chemical scenarios. A more homogeneous picture is seen for persons engaged, where the regionally cumulated changes under the vehicle and construction scenarios are relatively close (12 × 10^3 persons yr^{-1}, 10 × 10^3 persons yr^{-1}), while the textile and chemical scenarios account for a change of 4 × 10^3 persons yr^{-1} and –11 × 10^3 persons yr^{-1}, respectively (point estimates). Regionally cumulated point estimates for hours worked amount to 24 × 10^6 h yr^{-1}, 18 × 10^6 h yr^{-1}, 5 × 10^6 h yr^{-1}, –22 × 10^6 h yr^{-1} respectively (point estimates), under the vehicle, construction, textile, and chemical scenarios. For all labor indicators, temporal variation and Monte Carlo perturbation generate result intervals at the regional scale that do not cross the reference line to any relevant extent and thus underpin the change direction (sign) of the point estimates.

3.2. Capital compensation

The estimated changes in the vehicle, construction, and textile scenarios appear to be quite balanced in that the monetary amount of replaced inputs equals the monetary amount of replacing inputs. Under the chemical scenario, however, the replacing inputs consist of (low-value) residues. As part of the substitution, residues undergo valorization and thus enter the (monetary) system without affecting the upstream inputs associated with residue generation. Residue valorization can be interpreted as a source of potential extra revenue for the benefit of the residue suppliers. The largest cumulative capital compensation increases in EU-27, BRIC+, and NEMO, at 10 × 10^6 USD yr^{-1}, are obtained under the textile scenario (Fig. 4), indicating an expansion in operating surpluses and/or in the use of assets such as buildings and infrastructure, machinery and equipment, products of agriculture and forestry, and computer software (Timmer et al., 2007). However, when residue valorization is taken into account, the chemical (residue use) scenario exhibits a considerably higher net increase of 708 × 10^6 USD yr^{-1}. The vehicle and construction scenarios present minor negative changes of –7 × 10^6 USD yr^{-1} and –43 × 10^6 USD yr^{-1} respectively, while the chemical scenario reveals a reduction of –292 × 10^6 USD yr^{-1}, when residue valorization is disregarded (point estimates). Again,

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[2] Missing data for labor indicators and capital compensation in ROW (all sectors), China (Sale, Maintenance and Repair of Motor Vehicles and Motorcycles, Retail Sale of Fuel [50], Private Households with Employed Persons [P]), and Indonesia (50); missing data for hours worked and persons engaged in South Korea (P) Erumban et al. (2012).

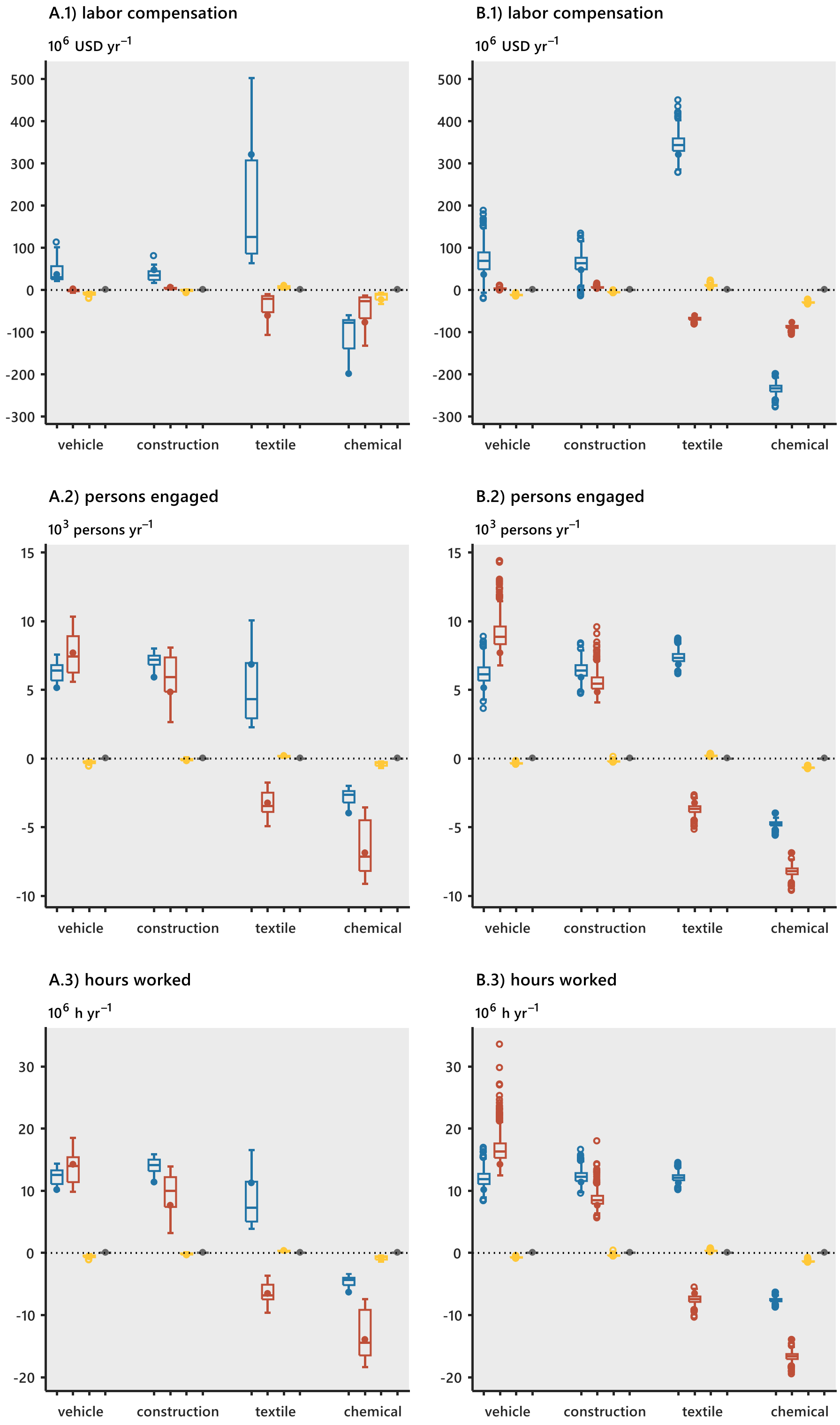

Fig. 3. Absolute changes in labor compensation (row 1), persons engaged (row 2) and hours worked (row 3) by region (EU-27 [blue]; BRIC+ [red]; NEMO [yellow]; ROW [gray]) under the respective substitution scenario. Filled circles represent point estimates for the year 2009. Boxplots include results for each year from 1995 to 2009 ($n = 15$) (column A) and for each of the Monte Carlo simulation runs based on year 2009 data ($n = 10^3$) (column B). Please note the data gaps declared in Footnote 2.

larger changes outside the EU-27 are induced in BRIC+ under the textile and chemical scenarios. Despite a fairly broad spectrum of results with respect to temporal variation, the change directions (signs) remain unambiguous in most cases. Under the vehicle and construction scenarios in the EU-27 region, temporal or Monte Carlo variation intervals are scattered around the reference line, thus indicating uncertainty with respect to the direction of change.

3.3. *Material use*

The combined regional changes for biomass use are largest under the vehicle and construction scenarios (0.59×10^6 t yr^{-1}, 0.56×10^6 t

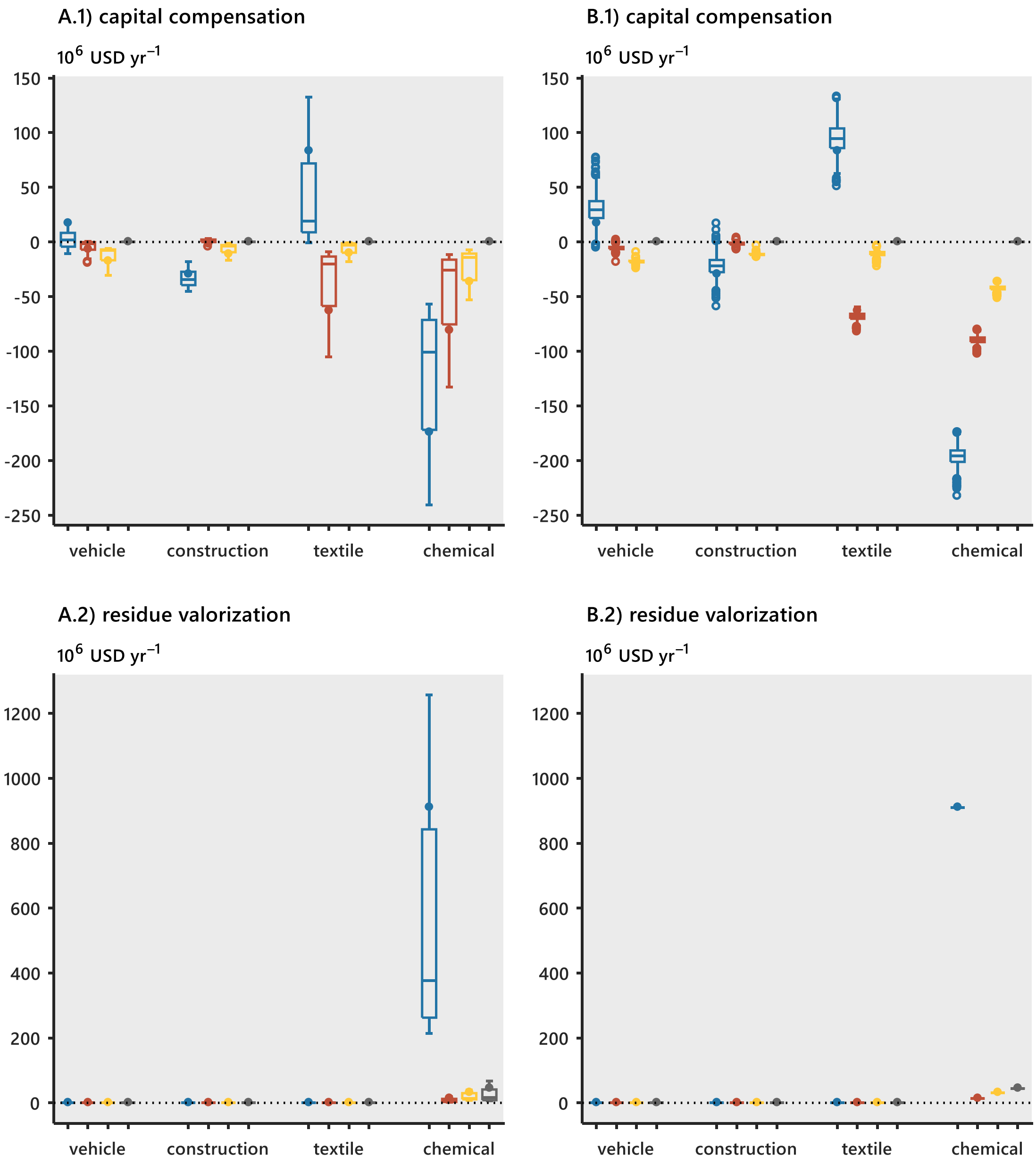

Fig. 4. Absolute changes in capital compensation (row 1) and residue valorization (row 2) by region (EU-27 [blue]; BRIC+ [red]; NEMO [yellow]; ROW [gray]) under the respective substitution scenario. Filled circles represent point estimates for the year 2009. Boxplots include results for each year from 1995 to 2009 ($n = 15$) (column A) and for each of the Monte Carlo simulation runs based on year 2009 data ($n = 10^3$) (column B). Please note the data gaps for capital compensation declared in Footnote 2.

yr^{-1}), where biomass includes primary crops, crop residues (used), fodder crops including grassland harvest, grazed biomass, wood, fish capture, crustaceans, molluscs and aquatic invertebrates, hunting and gathering (Eurostat, 2007) (Fig. 5). Additional biomass use reaches a lower level in the textile scenario (0.23 × 10^6 t yr^{-1}), while the changes induced under the chemical scenario are quite negligible (–0.04 × 10^6 t yr^{-1}) (point estimates). A relatively stable regional distribution pattern of biomass use growth is found across the non-residue use scenarios (vehicle, construction, textile). The non-biomass material aggregate – fossil and mineral resources – comprises brown coal including oil shale and tar sands, hard coal, petroleum, natural gas, peat, iron ores, non-ferrous metal ores, and non-metallic minerals (Eurostat, 2007). A significant reduction across all regions in fossil and mineral resource use occurs under the chemical scenario (–4.87 × 10^6 t yr^{-1}), followed in a fairly regular descending order by the textile (–3.95 × 10^6 t yr^{-1}), construction (–2.01 × 10^6 t yr^{-1}), and vehicle scenarios (–0.99 × 10^6 t yr^{-1}) (point estimates). The scenarios appear to form two distinct groups. In one group, significant reductions may be observed (textiles, chemicals), while in the other, the effects are consistently less pronounced (vehicle, construction except for EU-27). Whereas net changes are clearly positive (or negligible) with regard to biomass use, Monte Carlo simulation shows a much wider distribution of results for fossil and mineral resource use in EU-27 and NEMO, particularly in the construction (direction and magnitude) and chemical scenarios (magnitude). Fossil and mineral resource use deviates from other indicators in that it appears to be exceptionally sensitive to variations in flows at the sub-sectoral level, thus resulting in a greater range of uncertainty.

3.4. *Emissions to air*

At –1.21 × 10^6 t yr^{-1}, the total mitigation of CO_2, CH_4, and N_2O emissions to air – measured in CO_2 equivalents – is largest under the

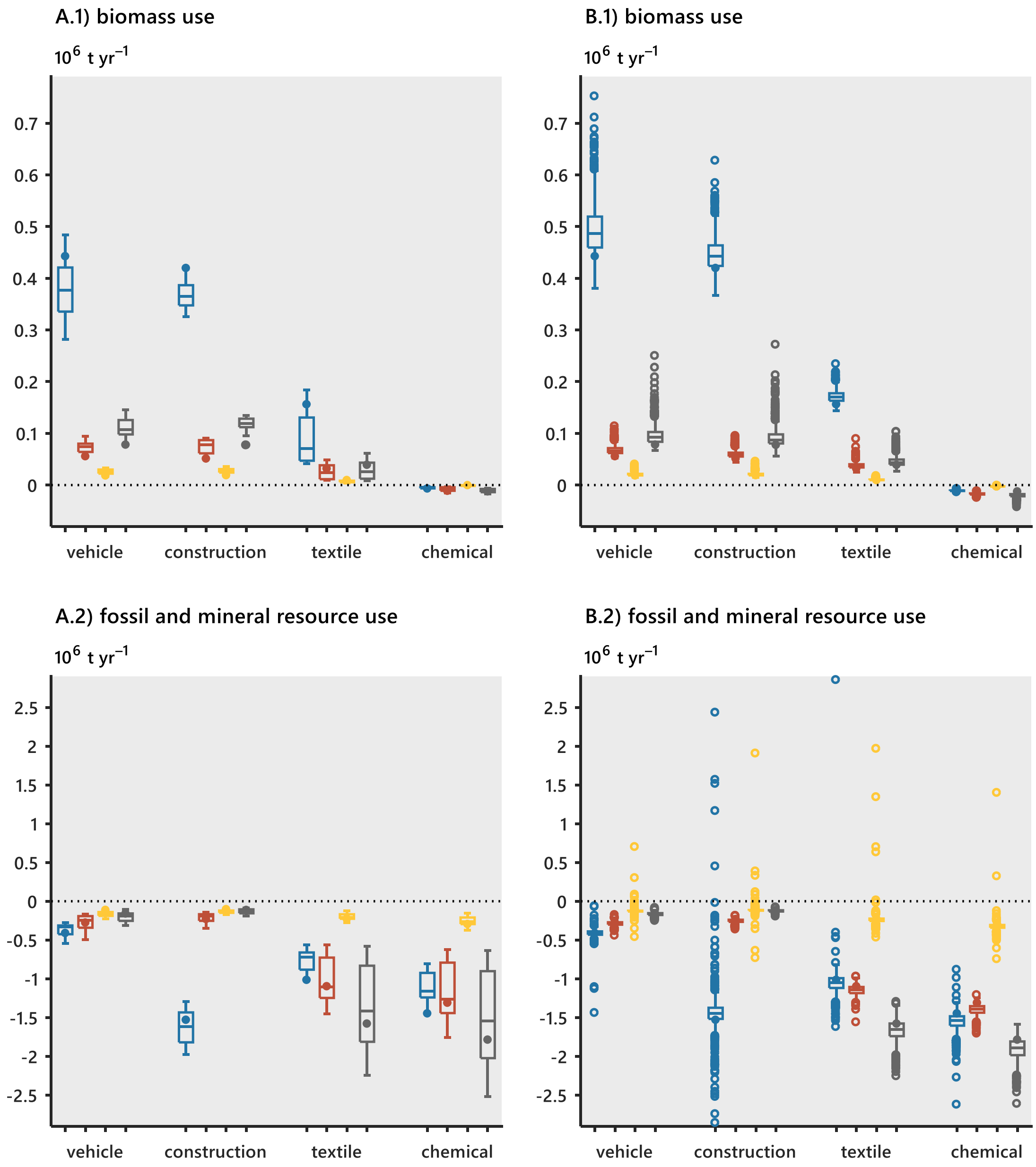

Fig. 5. Absolute changes in material use by type (rows 1–2) and region (EU-27 [blue]; BRIC+ [red]; NEMO [yellow]; ROW [gray]) under the respective substitution scenario. Filled circles represent point estimates for the year 2009. Boxplots include results for each year from 1995 to 2009 ($n = 15$) (column A) and for each of the Monte Carlo simulation runs based on year 2009 data ($n = 10^3$) (column B). Please note that some positive and negative outliers are not displayed in panel B.2 for EU-27.

chemical scenario (Fig. 6). Assuming substitution in the textile and construction sectors, a reduction of –0.47 × 10^6 t yr^{-1} and –0.46 × 10^6 t yr^{-1}, respectively, is achieved. The contribution to mitigation achieved under the vehicle scenario is estimated to be –0.14 × 10^6 t yr^{-1} (point estimates). The regional distribution pattern of emission mitigation correlates with that of fossil and mineral resource use, except for the EU-27 under the textile scenario, where irrespective of a decline in fossil and mineral resource use, the change direction of emissions to air appears to be positive. In contrast, the construction and chemical scenarios stand out in presenting a pronounced mitigation potential for the EU-27. Temporal and Monte Carlo variation intervals include the reference line in the EU-27 region under the textile and vehicle scenarios, indicating uncertainty concerning the direction of change in these cases. The same applies to the NEMO region under all non-residue use scenarios, although here the potential impact is of a relatively minor magnitude.

3.5. *Land use*

We use an aggregate bioproductive land use indicator that covers agricultural crop production, temporary meadows, gardens, and temporary fallow land, long-term crops production (e.g. coffee, roses, nurseries), permanent wild or cultivated herbaceous forage crops, and the forest area that is actually used for wood production (Genty et al., 2012). In principle, the assessment could be done for differentiated land use types. However, by reason of the sectoral resolution employed in WIOD, we choose to report at an aggregated level only. As the data shows, land use tends to be stable over time, and land conversions, if present, are long-term processes that do not reflect short-term output volume fluctuations. Thus, the immediate effects of short-term output volume changes in land-based production are changes in land use intensity rather than in land use area. The land use area increments presented here should be interpreted as the land requirement potentials

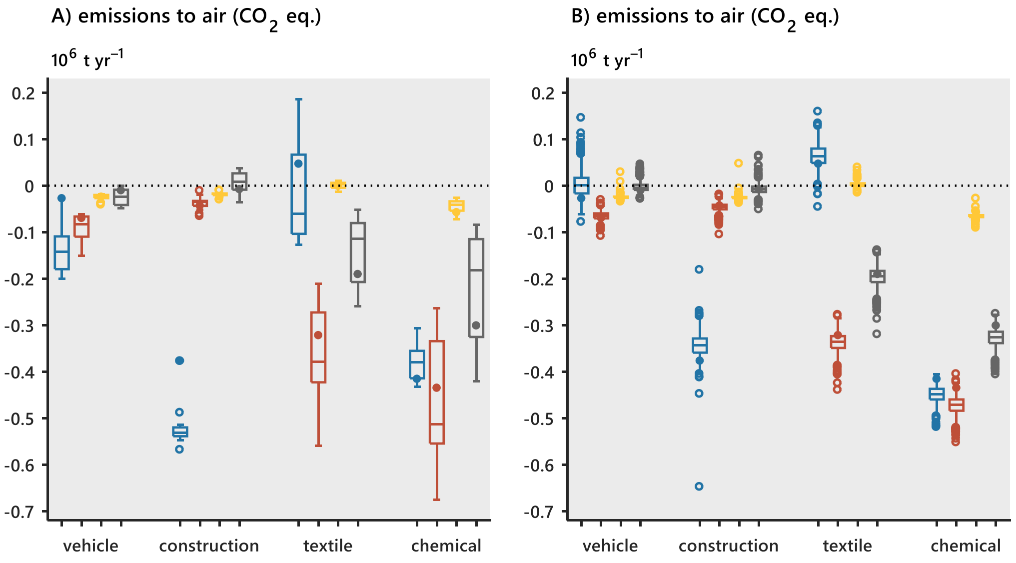

Fig. 6. Absolute changes in emissions to air by region (EU-27 [blue]; BRIC+ [red]; NEMO [yellow]; ROW [gray]) under the respective substitution scenario. Filled circles represent point estimates for the year 2009. Boxplots include results for each year from 1995 to 2009 ($n = 15$) (panel A) and for each of the Monte Carlo simulation runs based on year 2009 data ($n = 10^3$) (panel B).

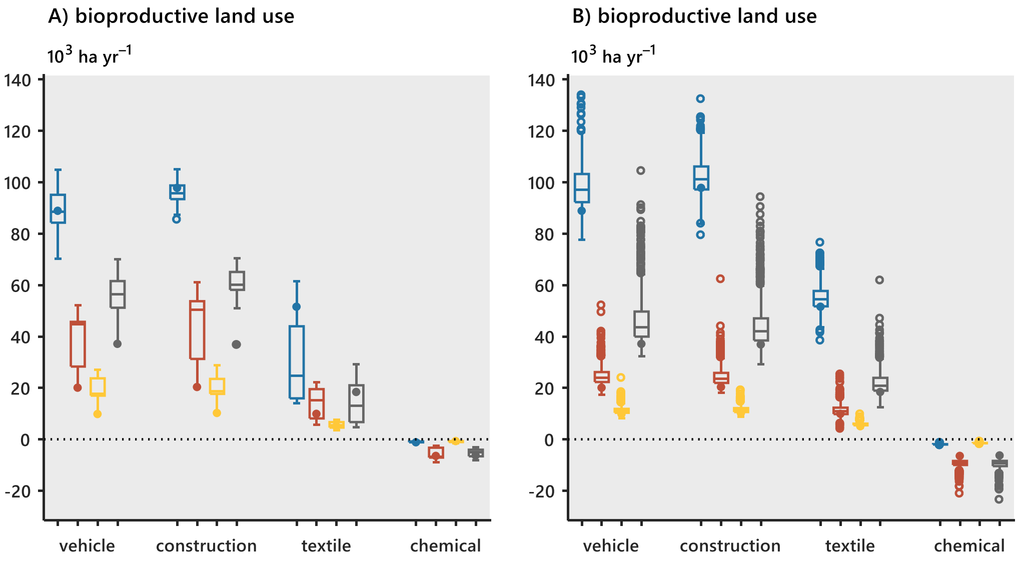

Fig. 7. Absolute changes in bioproductive land use (arable land, permanent crops, permanent meadows and pastures, and productive forest area) by region (EU-27 [blue]; BRIC+ [red]; NEMO [yellow]; ROW [gray]) under the respective substitution scenario. Filled circles represent point estimates for the year 2009. Boxplots include results for each year from 1995 to 2009 ($n = 15$) (panel A) and for each of the Monte Carlo simulation runs based on year 2009 data ($n = 10^3$) (panel B).

inherent in each substitution scenario, based on the land use intensity of the current year. With estimated changes of 164 × 10^3 ha yr^{-1}, and 155 × 10^3 ha yr^{-1} respectively, the construction and vehicle scenarios show the largest regionally cumulated impact on bioproductive land use (Fig. 7). A change of 84 × 10^3 ha yr^{-1} may be attributed to the textile scenario, while the change in the chemical scenario is negligible (–16 × 10^3 ha yr^{-1}) (point estimates). Bioproductive land use is closely related to biomass use. This is reflected in the similarity of their regional distribution patterns within the non-residue use scenarios, as well as in their relatively comparable level of inter-scenario divergences. While the temporal and Monte Carlo variation intervals for bioproductive land use appear to be larger than those of biomass use they still allow for confirmation of the signs of the point estimates.

3.6. *Water use*

The industrial use of water resources entails a variety of socio-economic and environmental implications. A distinction is commonly made between the terms blue water, green water, and gray water. Blue water use refers to the consumption of surface and ground water and is thus associated with issues of ecosystem scarcity. Green water is used to refer to the precipitation involved in crop production. gray water refers to the amount of freshwater necessary to assimilate pollutants based on existing quality standards, i.e. it is a measure of freshwater pollution (Aldaya et al., 2012; Genty et al., 2012). The textile scenario indicates an additional regionally cumulated blue water use of 16 × 10^6 m^3 yr^{-1}, followed by the vehicle and construction scenarios with 9 × 10^6 m^3 yr^{-1} each (Fig. 8). The chemical scenario shows a comparatively high savings potential of –20 × 10^6 m^3 yr^{-1}. The cumulated increase in green water use is highest in the vehicle and construction scenarios with 181 × 10^6 m^3 yr^{-1} each, while the increase in the textile scenario is at a significantly lower level (67 × 10^6 m^3 yr^{-1}). The changes in the chemical scenario are negligible (–16 × 10^6 m^3 yr^{-1}). With regard to gray water, summing changes across the regions shows that the textile scenario is particularly relevant (52 × 10^6 m^3 yr^{-1}), while among the vehicle, construction and chemical scenarios comparatively small increases or decreases are obtained (11 × 10^6 m^3 yr^{-1}, 8 × 10^6 m^3 yr^{-1}, –7 × 10^6 m^3 yr^{-1}) (point estimates). While blue and gray water use present rather unique distribution patterns, green water use is closely correlated with biomass and bioproductive land use. Temporal and Monte Carlo variation intervals include the reference line in some cases, indicating uncertainty with respect to the direction of blue and gray water use changes, mainly in ROW.

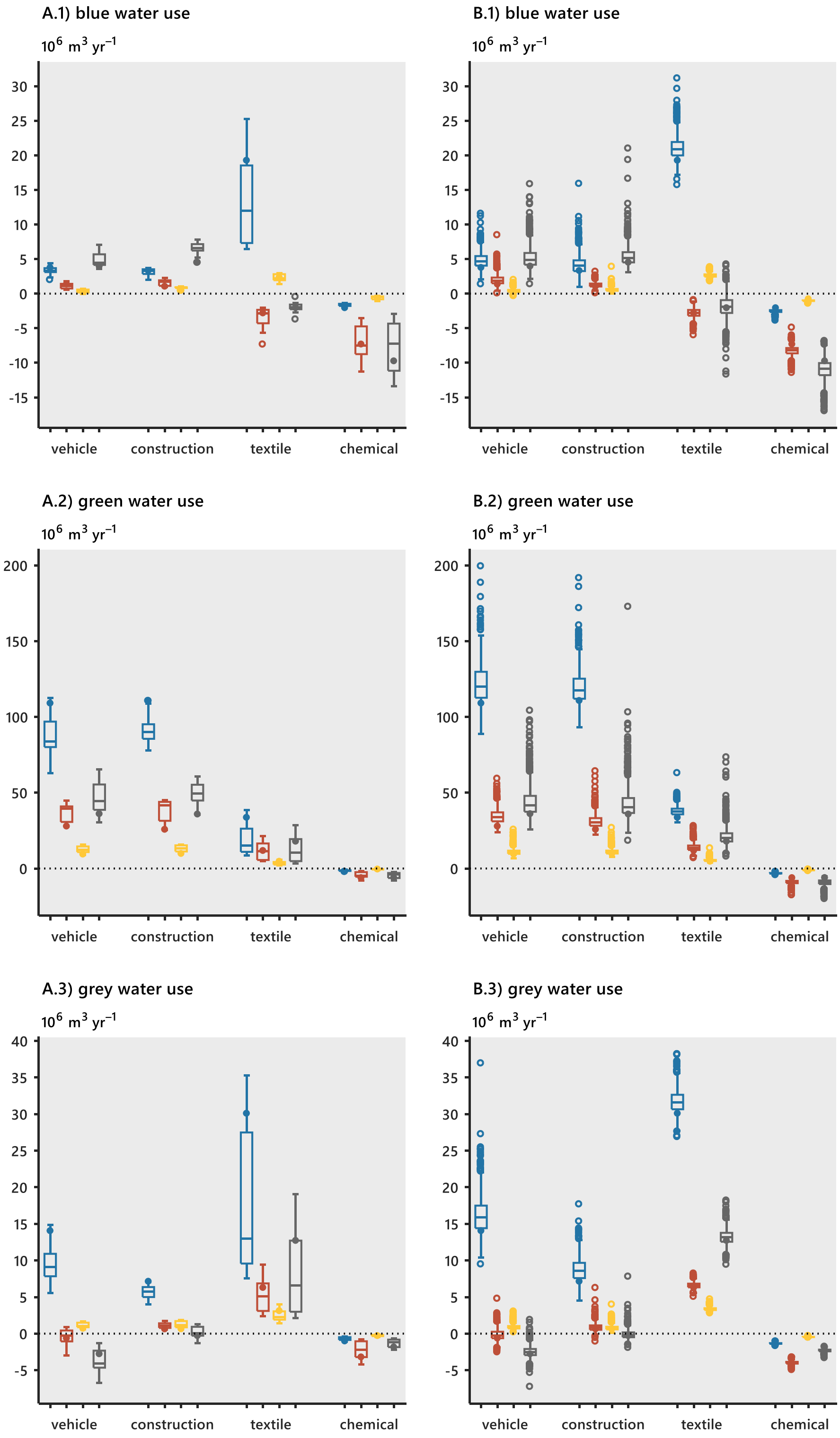

Fig. 8. Absolute changes in water use by type (rows 1–3) and region (EU-27 [blue]; BRIC+ [red]; NEMO [yellow]; ROW [gray]) under the respective substitution scenario. Filled circles represent point estimates for the year 2009. Boxplots include results for each year from 1995 to 2009 (n = 15) (column A) and for each of the Monte Carlo simulation runs based on year 2009 data ($n = 10^3$) (column B).

4. Discussion

The present study aims at presenting a comparative impact assessment of (potential) large-scale, bioeconomic, generic sectoral innovations, paying particular attention to the trade-offs between policy objectives. Increasing competition for biomass and land resources (Söderholm and Lundmark, 2009; O'Brien et al., 2017) raises the significance of cascading use (Haberl and Geissler, 2000; Essel and Reichenbach, 2016). This, in turn, implies a priority of material over energetic uses of biomass. We examined four substitution scenarios involving material uses of biomass in various applications, each with divergent requirements in terms of raw material quality. The cases studied cover varying degrees of maturity with regard to technological development and market diffusion. Wooden construction and wood-

Table. 7
Contribution to bioeconomy objectives under the four scenarios studied in the EU-27 countries (Y: yes, N: no, –: neutral).

Bioeconomy objective	Indicator	**EU-27**			
		vehicle	construction	textile	chemical
strengthening European competitiveness and creating jobs	+ changes in labor compensation	Y[2]	Y[2]	Y	N
	+ changes in persons engaged	Y	Y	Y	N
	+ changes in hours worked	Y	Y	Y	N
	+ changes in capital compensation	Y[1]	N[2]	Y	Y[3]
reducing dependence on non-renewable resources, mitigating and adapting to climate change	– changes in fossil and mineral resource use	Y	Y[2]	Y[2]	Y
	– changes in emissions to air	Y[2]	Y	N[1,2]	Y
managing natural resources sustainably and ensuring food and nutrition security	– changes in biomass use	N	N	N	–
	– changes in land use	N	N	N	–
	– changes in water use	N	N	N	–

[1] Uncertain result (temporal variation).
[2] Uncertain result (Monte Carlo simulation).
[3] Under the assumption of residue valorization.

based textile fibers are relatively well-developed applications, while wooden structural components in vehicles and lignin-based chemicals are currently still under development (Hurmekoski et al., 2018a). In line with Rose and McNiven (2007), a transition to a bioeconomy is expected to have the most impact in substitution processes that reconfigure raw material flows at a significant scale. The case selection thus excludes low-volume bio-based applications such as pharmaceutical products or food additives (Hetemäki, 2014). Three of the four cases (construction, textiles, chemicals) are explicitly mentioned in the EU bioeconomy strategy as opportunities for the forest sector (European Commission, 2018).

Table 7 summarizes the potentials and limitations of the innovations to contribute to policy objectives in the EU-27 countries. Our results point to a number of possible benefits regarding all policy objectives considered here. However, there is an astonishing diversity of outcomes across the scenarios. In order to illustrate and discuss this diversity, we focus on those results that are in disagreement with the EU bioeconomy strategy (European Commission, 2018) and thus are unexpected from the point of view of the dominant narrative of bioeconomy. The discussion is structured by several factors that led to the occurrence of such unexpected results in the context of this study. It is not our aim to present an exhaustive list of obstacles to innovation related to bioeconomy policy.

4.1. Competing goals and domestic displacement effects

The concept of the competing goals dilemma (Boehlje and Bröring, 2011) refers to the existence of trade-offs between the economic, social and environmental dimensions associated with bio-based innovation. As far as the scenarios examined here are concerned, our results confirm that there is a high degree of goal competition. This is indicated by the ambivalence that all scenarios show, at least to some extent, with regard to their socioeconomic and ecological impact in the EU-27. The most prominent manifestation in this respect is found under the chemical scenario, where environmental impact reduction is accompanied by marked declines in labor indicators. The explanation is straightforward. Efficiency gains induce – ceteris paribus – an actual reduction in inputs, which has an indirect dampening effect on resource use, emissions, and labor input, along the supply chain. In contrast to the other scenarios, desirable and undesirable effects are not mitigated by the use of a substituting product. Thus, the exploitation of previously unused residues or capacities as substitutes tends to be both effective and conflictual. In contrast, product substitutes may cause rather large displacement effects in both socioeconomic and environmental terms. For example, as our results show on country- and sector-specific level, net gains in labor compensation under the vehicle and construction scenarios are relatively small since a major fraction of the additional labor needed in bio-based supply chains is balanced out by a labor decline for conventional suppliers. Similarly, the consumption of fossil and mineral resources is reduced in one place and increased in another.

The results of the present study not only show trade-offs between, but also within the groups of socioeconomic and environmental indicators. The construction scenario indicates a negative correlation for labor indicators and capital compensation in the EU-27. This is due to the differences between conventional and bio-based suppliers in capital compensation per unit of output. Moreover, while here the additional use of bio-based inputs is accompanied by an increase in labor along the supply chain, such indirect effects play almost no role in capital compensation. It has to be noted that the Monte Carlo simulation result intervals for labor and capital compensation include the reference line, indicating uncertainty of this finding. As far as the group of environmental indicators is concerned, the textile scenario shows a negative correlation between emissions and fossil and mineral resource use in the EU-27. We explain this by the fact that increased use of biogenic raw materials is associated with a partial relocation of supply chains into the EU-27. While domestic emissions increase accordingly, domestic fossil resource use is far less affected as a result of high import shares. The scenario-induced reduction of fossil-based inputs, on the other hand, mitigates emissions and resource use more evenly, as both indicators react only moderately here. In sum, then, under the textile scenario, emissions in the EU-27 increase, while fossil and mineral resource use decrease. However, this trade-off does not show up in every year investigated and not in every Monte Carlo simulation run, which emphasizes the uncertainty associated with this finding and calls for further research.

4.2. Regionally inverse effects

National and supranational policy goals are usually related to a certain geographical area. For example, the GHG emission reduction targets of the EU member states refer exclusively to direct emissions originating within their respective national territories (European Union, 2018). However, such territorially delimited approaches fail to take account of leakage effects in other regions. There is empirical evidence that industrialized countries are increasingly outsourcing resource-intensive industries to emerging economies (Krausmann et al., 2017). While this reduces domestic direct emissions it does not bring about actual savings at the global level. Conversely, emission mitigation may be achieved through innovation without benefiting domestic emission inventories. This is found to be the case under the textile scenario, where emissions rise in the EU-27 and at the same time decrease globally (point estimates). Other indicators also show divergencies in the changes prevailing in the respective regions. A comparison of EU-27 and BRIC+ under the textile scenario reveals a number of inverse effects, reflecting the corresponding exchange relations between the regions. While blue water use, capital compensation and all labor-related indicators increase in EU-27, they decrease in BRIC+, which is mostly caused by a relocation of production activity into EU-27 in the textile scenario. Temporal variation and Monte Carlo simulation result intervals largely confirm the signs of the point estimates. Regional deviations in effect direction are also present among other scenarios– e.g. gray water use under the vehicle scenario – but are less relevant in terms of frequency and magnitude.

4.3. Decoupling of value creation and fossil resource use

Increasing affluence, or value creation, is regarded as the main driving force behind the per capita use of material, with higher income elasticities reported for fossil resources than for biomass (Steinberger et al., 2010; Wiedmann et al., 2015). Assuming these elasticities obtain under the Shared Socioeconomic Pathway projections (Riahi et al., 2017), a rapid increase in the use of fossil resources is to be expected during the coming decades in Europe, despite a simultaneous growth in biomass use (Asada et al., 2020). Such a development would obviously be in conflict with several targets of the European bioeconomic strategy, in particular, with the objectives of reducing fossil resource dependency and mitigating climate change. Whether or not these objectives seem feasible depends largely on the extent to which wealth creation and fossil resource use can be decoupled. In this regard, the innovations studied present widely differing outcomes despite rather homogeneous scenario assumptions such as a fixed substitution value. Both in the EU-27 and globally, a positive net change in value added is shown under all scenarios when residue valorization is taken into account. However, those replacing low-processed fossil-based inputs (textiles, chemicals) appear to have a greater potential for decoupling value creation from fossil (and mineral) resource use. A valid reason seems to be that the higher the processing level and value of the replaced product, the more value added – and thus the less material input volume – is reduced at a given substitution value along the conventional supply chain. From this perspective, the processing levels of the products involved in the substitution play an important role in the decoupling potential of bioeconomic innovations. With respect to the four cases assessed, it should be noted that owing to the sectoral structure employed in the WIOD, no distinction is made between fossil and mineral resource use in the present study. In addition, the indicator is subject to rather large uncertainties as the Monte Carlo simulation intervals range widely from negative to positive for some regions and scenarios. Given the relevance of decoupling wealth creation and fossil resource use for the bioeconomy, there is a clear need for further research on this aspect.

4.4. Assumptions and limitations

The approach chosen in this study is based on a number of assumptions and therefore exhibits certain limitations. First, the system boundaries of the present analysis exclude the use and end-of-life phases of product life cycles. Our approach might thus be unable to fully capture the substitution impacts occurring downstream in the supply chain. For example, the end-of-life of wood products is estimated to account for a third of its climate change substitution effect on average due to the CO_2 emission savings from energy recovery (Leskinen et al., 2018). Second, linearity is assumed regarding input-output relations and output-indicator relations. This implies that potential production constraints are not taken into account and substitutions lead neither to new products nor to technological changes elsewhere in the economy. As a characteristic of the linear model, returns to scale and prices are constant and rebound effects or comparable systemic responses are not considered. The linearity assumption is considered acceptable for the study of marginal changes (Yang and Heijungs, 2018) and seems to be justified given the relatively small changes occurring under the scenarios assessed. However, one should refrain from scaling up the results to higher orders of magnitude – a tenfold increase in substitution value does not necessarily lead to a tenfold increase in substitution effects. Third, the assessment focuses on the changed input flows as a consequence of technology change and not on the implementation of new technologies as such. The direct impacts occurring in the substituting sectors are not taken into account, e.g. labor compensation per output unit is equal before and after the substitution. Yet, the indicator levels can change indirectly as a consequence of output changes in that sector. We expect that the consideration of implementation activities would tend to influence the results in a positive direction, leading to weaker decreases and stronger increases in the indicators. Fourth, for specific innovation cases on the sub-sectoral level, environmental net impacts may be underestimated and socioeconomic effects overestimated as the sub-sectoral material flows involved in substitution are likely to be higher in volume and lower in value than the sector averages. The Monte Carlo simulation shows that results for sub-sectoral substitution cases may deviate – in some indicators substantially – from the sectoral average. On the other hand, most of the results do not show uncertainty regarding the direction of change. Fifth, with regard to the chemical scenario it is assumed that energy losses resulting from lignin-utilization other than for energy generation can be compensated by increases in the energy-efficiency of pulp mills, as, for example, stated by Holladay et al. (2007). In summary, we consider the assumptions to be reasonable for the purpose of this study. The modeling of a more substantial shift towards bioeconomy, in contrast, would require to take into account fundamental changes in the economic structure caused by large-scale reconfigurations of resource use patterns. This would necessitate a revaluation of the approach.

5. Policy implications and conclusions

Technology-neutral climate policies are often regarded as preferable over technology-specific ones as they draw on market mechanisms for resource allocation (Söderholm and Lundmark, 2009; Azar and Sandén, 2011). On the other hand, technology-specific innovation policy is perceived as being a meaningful (and necessary) complement to technology-neutral policies, e.g. in order to bridge risky and costly commercialization phases (Azar and Sandén, 2011; Hellsmark and Söderholm, 2017; Lazarevic et al., 2019). This latter view is reflected in the EU bioeconomy strategy, whose central pillar is innovation as a driving force of change. The attempts at identification of individual technologies, applications, and sectors, as well as the fact that technology-neutral measures are largely absent, point to the predominantly specific and selective character of the strategy. As the strategy is also intended as a blueprint for subsequent national action plans of EU member countries (European Commission, 2018), technological, sectoral, and innovation-related selectivity will play a role there as well. Exploring the potential impacts of bio-based innovations, and their capacity to contribute to the achievement of policy objectives, is thus of high relevance for European bioeconomy development.

In this study, we estimated the socioeconomic and environmental impacts of four bio-based generic sectoral innovations in an integrated, holistic and comparative MRIO-based assessment. We demonstrated the applicability and limits of the approach and derived policy-relevant insights by contrasting the results with the EU bioeconomy strategy. Our results reflect the expected beneficial impacts of such a strategy in a number of ways, and along various dimensions of sustainability. We found, however, that each innovation exhibits its own profile with regard to potentials and limitations of contributing to policy objectives. Our study is by no means exhaustive, as other bio-based innovations might have other impacts, both positive and negative, and further sectors and indicators are worth to be explored in future research studies. Nevertheless, it is clear from the available results that decisions on future utilization paths of biomass will strongly influence the characteristics of an upcoming bioeconomy in terms of sustainability. Such decisions can either be left to markets, which, under externality of environmental costs, is likely to cause distortion in favor of socioeconomic objectives and to the detriment of environmental ones. Or, a more favorable option is chosen by strategically defining innovation portfolios to be fostered, based on scientific evidence. We conclude by stating that the mere promotion of additional biomass use as a policy strategy is not sufficient to pursue the development of an effective bioeconomy capable to deliver "sustainable growth."

CRediT authorship contribution statement

Raphael Asada: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Giuseppe Cardellini:** Writing - original draft, Writing - review & editing. **Claudia Mair-Bauernfeind:** Writing - original draft, Writing - review & editing. **Julia Wenger:** Writing - original draft, Writing - review & editing. **Verena Haas:** Writing - original draft. **Daniel Holzer:** Writing - original draft. **Tobias Stern:** Conceptualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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