Bioeconomic transition?
Projecting consumption-based biomass and fossil material flows to 2050

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Abstract
Countries are responding to unsustainable resource extraction, rising emissions, and increasing waste streams by implementing national bioeconomy strategies. Assuming that the purpose of a bioeconomy is to replace fossil use by biogenic resource use, we estimate biomass and fossil raw material consumption (RMC) by applying multiregional input–output methodology for middle and high income countries. Next, we use a panel fixed effects model to explain RMC with economically active population, urban population, GDP, land cover, and fossil/biomass domestic material consumption. With this model, we project RMC under five Shared Socioeconomic Pathway scenarios up to 2050. The projections show an increase in per capita biomass RMC between 2010 and 2050, accompanied by—in many cases pronounced—per capita growth of fossil RMC across most of the countries and scenarios. We conclude that, if GDP continues to drive fossil RMC at its current magnitude, upcoming conditions are likely to counteract a potential bioeconomic transition and increase, instead of decrease, fossil RMC. Thus, increasing biomass use will not necessarily lead to reduced fossil resource consumption. When considering the relative scarcity of biomass, land and water, more focus needs to be placed on the relevance of technological bio-based innovations in the reconfiguration of RMC drivers.

KEYWORDS
bioeconomics, decoupling, industrial ecology, input–output analysis (IOA), societal metabolism

1 | INTRODUCTION

Factors such as insufficient material efficiency gains in middle and high income countries, the rapid economic growth of emerging economies, and the unsustainable extraction of finite natural resources, have all contributed to raising the significance of emission and waste issues on a global scale (Krausmann, Schandl, Eisenmenger, Giljum, & Jackson, 2017). In response, countries have formulated source and sink-related reduction policies (EEA, 2016; UNEP, 2017), among which bioeconomy strategies combine arguments from various meta-discourses such as limits to growth, ecological modernization, neoliberalism, and sustainable development (Pülzl, Kleinschmit, & Arts, 2014). The currently dominant interpretation of bioeconomy is that of a "biomass-based economy" (Vivien, Nieddu, Befort, Debref, & Giampietro, 2019) as opposed to a "fossil-based economy". From this viewpoint, the intentional and unintentional effects of a supposed bioeconomic transition are described in terms of a gradual reduction of fossil resource use, facilitated by an intensified use of biomass. This process is related to environmental changes involving emissions to air, land, and water use, biogenic carbon storage, finite resource depletion, biodiversity (Clancy, Fröling, & Svanström, 2013; Pawelzik et al., 2013), eutrophication, ozone depletion (Weiss et al., 2012), as well as the accompanying socioeconomic changes in primary energy use (Weiss et al., 2012), operating...
costs and assets, health and safety, employment opportunities, participation, culture and recreation, and social rights (Clancy et al., 2013). Thus, a bioeconomic transition is expected to bring about a clear shift in environmental and socioeconomic benefits and burdens across space, which emphasizes the significance of current and future material use patterns.

Although several national and supranational strategy papers on the concept of a bioeconomy have recently been formulated in Europe, the Americas, Asia, and Africa, considerable variation in terms of definitional scope still remains (Biber-Freudenberger, Basukala, Bruckner, & Börner, 2018; Bracco, Calicigioglu, Gomez San Juan, & Flammini, 2018; Hausknost, Schriefl, Lauk, & Kalt, 2017; Priefert, Jörissen, & Frör, 2017). While some strategies focus on traditional biomass production and processing sectors, such as forestry and the pulp and paper industry, others highlight the significance of innovations in the high-tech sectors to develop the bioeconomy of the respective country (Beermann, Jungmeier, Pignatelli, Monni, & Van Rees, 2015; Dubois & Juan, 2016; Püzl et al., 2014). Strategies also tend to vary in terms of objectives (Lusser et al., 2018) and measurement frameworks, and gaps between target formulation and indicator selection have been observed repeatedly (Bracco et al., 2018). On a more general level, however, there does appear to be considerable consensus regarding the expected outcomes of bioeconomic growth. These include a reduction in fossil resource dependency, an increase in industrial use of biogenic resources, climate change mitigation, improved energy security, and the creation of employment and economic development in rural areas. Criticism of the concept mainly centers on the difficulties involved in ensuring sufficient availability of biomass while maintaining functioning ecosystem services and food security, rather than with the stated outcomes per se. In other words, criticism tends to focus on the potential biophysical limits to bioeconomic growth (Priefert et al., 2017).

Globally, fossil resource extraction grew from $6.2 \times 10^9$ metric tons (t) in 1970 to $14.4 \times 10^9$ t in 2014, while biomass harvest increased in the same period from $8.8 \times 10^9$ t to $21.2 \times 10^9$ t. There has also been an associated shift in material extraction from Europe and North America to the Asia-Pacific region (International Resource Panel, 2017). This observation reflects an incremental externalization of resource-intensive industries by high income countries over recent decades, leading to an apparent relative or absolute material use decline in such economies (Dittrich, Bringezu, & Schütz, 2012; Krausmann et al., 2017; Wiedmann et al., 2015). However, a perspective that only considers direct material consumption is insufficient and needs to be complemented by the telecoupling effects relating to international trade (Gijum, Bruckner, & Martínez, 2015; Schaffartzik, Eisenmenger, Krausmann, & Weisz, 2014). Accordingly, some recent studies suggest that the state of bioeconomies should be monitored, among other things, based on resource footprint indicators including raw material consumption (RMC) flows (Biber-Freudenberger et al., 2018; Egenolf & Bringezu, 2019; O’Brien, Wechsler, Bringezu, & Schaldach, 2017) as a central assessment metric. Given such a background, the following questions arise: (a) how does the prevailing configuration of RMC drivers affect material use patterns in middle and high income countries, (b) to what extent is a future shift from fossil to biomass RMC to be expected in these countries, and (c) how sensitive are the results to alternative scenario assumptions? To this end, we estimate recent fossil and biomass RMC for a sample of economies and identify the associated key driving forces. On this basis, we project future resource use adopting the current drivers within Shared Socioeconomic Pathway scenarios and then draw related conclusions concerning the prospect of a future bioeconomic transition.

2 | METHODS

The methodology applied in this research is threefold. First, we estimate recent fossil and biomass economy-wide raw material consumption (RMC) for selected countries using an environmentally extended multiregional input–output approach (EEMRIO). Fossil RMC embraces lignite (brown coal), hard coal, oil shale and tar sands, peat, crude oil, condensate and natural gas liquids (NGL), and natural gas. Biomass RMC includes crops, used crop residues, grazed biomass, wood, wild fish catch, aquatic plants/animals, hunting and gathering (Eurostat, 2013). Second, we identify the current key driving forces of fossil and biomass RMC by setting up panel fixed effects (FE) models. Third, we project future fossil and biomass RMC under adoption of the current driving and mitigating forces using the Shared Socioeconomic Pathways (SSP) framework.

2.1 | Estimating recent fossil and biomass RMC

Multiregional input–output analysis is a useful tool for allocating unevenly distributed environmental and socioeconomic impacts to regional final consumption (Wiedmann, Wilting, Lenzen, Lutter, & Palm, 2011). Numerous studies have used environmentally extended multiregional input–output analyses (EEMRIO) for analyzing consumption-based allocation of raw materials (e.g., Bruckner, Gijum, Lutz, & Wiebe, 2012; Budzinski, Bezama, & Thrän, 2017; Eisenmenger et al., 2016; Gijum et al., 2015; Pothen, 2017; Schoer, Wood, Arto, & Weinzettel, 2013; Wiedmann et al., 2015). Such analyses have shown that estimations of RMC (Eisenmenger et al., 2016) or GHG footprints (Moran & Wood, 2014; Owen, Steen-Olsen, Barrett, Wiedmann, & Lenzen, 2014; Steen-Olsen, Owen, Hertwich, & Lenzen, 2014; Wieland, Gijum, Bruckner, Owen, & Wood, 2018) may differ depending on variations in sectoral aggregation levels and construction principles of the input–output database used. To improve the credibility of results we have chosen two quite different input–output databases, EORA and WIOD (see Supporting Information S1), and use RMC estimates derived from each of the databases for independent projections. Both databases were applied recently to estimate RMC or derived indicators (see, e.g., Pothen, 2017; Wiedmann et al., 2015).
Formally, we calculate RMC according to the standard EEMRIO model (Equation (1)), as described by, for example, Moran and Wood (2014), Pothen (2017), Schaffartzik et al. (2014), and Schoer, Weinzettel, Kovanda, Giegrich, and Lauwigi (2012). Thus:

\[ M = F(I - A)^{-1}Y \]  

(1)

where \( M \) is the RMC estimate, \( F = E \text{diag}(x)^{-1} \) denotes the material extension, \((I - A)^{-1}\) is the Leontief inverse with \( I \) as an identity matrix, \( A = Z \text{diag}(x)^{-1} \) is the input coefficient matrix, and \( Y \) is the \( mn \) by \( m0 \) final consumption matrix showing the monetary flows from \( o \) different final consumption classes (e.g., household and government expenditures) in \( m \) countries to the selling \( n \) sector in \( m \) countries. The \( p \) by \( mn \) matrix \( E \) quantifies the amount of \( p \) raw material types extracted from the domestic environment by \( n \) sectors in \( m \) countries in mass units. Vector \( x = Z \text{diag}(x)^{-1} \) represents sector-wise gross outputs, where \( s \) is a column vector of ones and the \( mn \) by \( mn \) matrix \( Z \) symbolizes a multiregional input–output square matrix containing inter-industry flows between \( m \) countries and \( n \) sectors. Each element \( z_{ij} \) denotes a monetary flow in the reference year with \( k = 1, \ldots, m \) (selling countries), \( I = 1, \ldots, I \text{ (purchasing countries)}, i = 1, \ldots, n \) (selling sectors), \( j = 1, \ldots, n \) (purchasing sectors). We aggregate the resulting \( p \) by \( m0 \) \( M \) matrix over the \( o \) final consumption classes country by country as well as over some groups within the \( p \) raw material types (e.g., biomass feed and biomass food). While we conduct the EEMRIO analysis as described with the WIOD Release 2013 (Dietzenbacher, Los, Stehrer, Timmer, & Vries, 2013), we use a pre-calculated footprint summary for EORA-based RMC estimations (Lenzen, Moran, Kanemoto, & Geschke, 2013), available online (KGM & Associates Pty. Ltd., 2018).

### 2.2 Identifying the driving forces of fossil and biomass RMC

Bioeconomic driving forces can be defined as direct or indirect factors affecting the level of an economy’s resource use in a multidirectional process (Steger & Bleischwitz, 2011). Drivers of domestic material consumption (DMC) have been investigated in multiple studies (e.g., Schandl & West, 2010; Steger & Bleischwitz, 2011; Steinberger, Krausmann, & Eisenmenger, 2010; for an overview see also Krausmann et al., 2017). In contrast, relatively little research has been done on the drivers of RMC. Two different approaches are used in the literature, structural decomposition analysis (SDA) (Plank, Eisenmenger, Schaffartzik, & Wiedenhofer, 2018; Pothen, 2017) and regression-based approaches (Teixidó-Figueras et al., 2016; Wiedmann et al., 2015). Pothen (2017) provides a global SDA with regard to RMC, quantifying the weight of the final demand, structural changes, and changes in the material intensity of extractive sectors, whereas Plank et al. (2018) focused on the impact of international trade on RMC. Teixidó-Figueras et al. (2016) and Wiedmann et al. (2015) conducted cross-sectional regression studies on RMC drivers including GDP, domestic raw material extraction (DE), population density, economically active population share, urban population share, ecosystem productivity, and climate. The present study follows the regression type of RMC driver analysis but uses longitudinal panel data to control for unobserved time-invariant heterogeneity. In accordance with Teixidó-Figueras et al. (2016) and Wiedmann et al. (2015), all variables are normalized by population to remove population size effects and to allow for international comparability. As a starting point for model specification, we use the set of drivers from Teixidó-Figueras et al. (2016), which we adapt as follows. First, we consider climate as invariant within countries across time (1995–2008) and therefore exclude it. Second, we use available forests/cropland and pastures as a proxy for ecosystem productivity, which allows us to use the SSP framework for projections. As this already controls for population density, we do not include the latter as an additional explanatory variable. Third, unlike in other studies, we include (production-based) DMC, differentiated by material category, as a candidate predictor of (consumption-based) RMC. So far it is unclear whether and how changes in the material intensity of production infrastructures affect RMC; nevertheless, it seems possible that variations in DMC—for example, due to the implementation of policy instruments—may lead to changes in RMC that are largely independent of other explanatory variables. Variance inflation factors (VIFs) within an acceptable range (Hair, Babin, Anderson, & Black, 2014) suggest that the risk of multicollinearity-related problems is tolerable (see Tables 3 and 4 for maximum VIFs).

Table 1 provides an overview of the variables considered. In line with the previous literature, we use GDP as a proxy for individual mean income, which we expect to have a positive impact on RMC (Teixidó-Figueras et al., 2016). The economically active population, represented by the age cohort of 15–64 year olds, is reported to have a positive impact on material use (Teixidó-Figueras et al., 2016). However, this is only partially confirmed by other analyses (Rosa & Dietz, 2012). A positive association of the urban population with urban growth and material use seems conceivable, but earlier studies also hypothesize that cities may be subject to economies of scale and thus mitigate consumption of materials (Teixidó-Figueras et al., 2016). For forests/cropland and pastures, we anticipate a positive relationship with biomass RMC and a negative link with fossil RMC. For DMC, which represents the production-side inputs to economies, we assume positive couplings within each material category, for example, a growing biomass DMC is supposed to come with an increasing biomass RMC.

As further drivers of RMC may appear plausible, but are difficult to measure directly (e.g., gradual, slow-moving institutional [Roland, 2004] and technological change with large variation across countries), we use an unobserved effects panel data model. Compared to cross-sectional regression, its major advantage is the ability to control for unobserved time-invariant heterogeneity, which substantially reduces the risk of omitted variable bias. We consider fixed effects (FE), random effects, and between effects estimators (Álvarez, Barbero, & Zofío, 2017). The FE estimator is reported since random effects estimators are preferably used for inferring observed sample effects (Searle, Casella, & McCulloch, 2009) whereas
### TABLE 1  Overview of variables included in the study

| Variable class          | Variable (short name)                                      | Description                                      | Unit                  | Source                          |
|-------------------------|------------------------------------------------------------|--------------------------------------------------|-----------------------|---------------------------------|
| Socioeconomic drivers   | Economically active share of population (active population)| Population ages 15–64 % of total                 | % of total            | World Bank (2018)               |
|                         | Urban share of population (urban population)                | Urban population                                 | % of total            | World Bank (2018)               |
|                         | GDP per capita (GDP)                                       | GDP, PPP                                          | 10^3 constant 2011 international $/cap | World Bank (2018)               |
| Land cover              | Pasture area per capitaa (pastures)                        | Permanent meadows and pastures                    | ha/cap                | FAO (2017)                      |
|                         | Forest and cropland area per capitaa (forests/cropland)    | Forest plus arable land and permanent crops       | ha/cap                | FAO (2017)                      |
| Material use            | Fossil domestic material consumption/cap<sup>a,b</sup> (fossil DMC) | Production-based fossil resources use             | t/cap                 | International Resource Panel (2018) |
|                         | Bio-based domestic material consumption per capita<sup>a,b</sup> (biomass DMC) | Production-based biomass use                      | t/cap                 | International Resource Panel (2018) |
| Material consumption    | Fossil raw material consumption per capita (fossil RMC)     | Consumption-based fossil resources use            | t/cap                 | EORA/WIOD (see Supporting Information S1) |
| (response variables)    | (EORA/WIOD)                                                |                                                  |                       |                                 |
|                         | Biomass raw material consumption per capita (biomass RMC)   | Consumption-based biomass use                     | t/cap                 | EORA/WIOD (see Supporting Information S1) |
|                         | (EORA/WIOD)                                                |                                                  |                       |                                 |

<sup>a</sup> SSP projections for this variable are available as regional aggregates (Asia, Latin America, OECD, former Soviet Union). To obtain disaggregated projections, we updated the most recent empirical data of each country by applying the projected growth rates of the corresponding region.

<sup>b</sup> SSP projections for this variable are not available. As proxies we apply fossil total primary energy supply (fossil TPES) for fossil DMC and the production of agricultural crops for biomass DMC.

FE estimators are rather applied to provide projections based on observed sample effects. All model variants are based on balanced panels. For FE estimation, data is used in de-meaned form (within-transformation) to perform ordinary least squares (OLS) regression with

\[
y_{it} = a_i + x_{it} \beta + \epsilon_{it}
\]

for years \( t = 1, \ldots, T \) and sample countries \( i = 1, \ldots, N \), where \( y_{it} \) represents the response variable (e.g., EORA-based fossil RMC), \( a_i \) denotes the country-specific time-invariant effects, \( x_{it} \) is the 1 by \( k \) vector of explanatory variables, \( \beta \) is the corresponding vector of parameters and \( \epsilon_{it} \) is the error term, which is assumed to be identically and independently normally distributed with zero mean and \( \sigma^2 \) variance. Besides setting up the full FE models for fossil and biomass RMC including all predictors, we use model selection to balance out a preferably low number of predictors with a preferably high goodness of fit. Best models were selected according to the Akaike information criterion (AIC) from a pool of all possible predictor combinations, calculated as

\[
AIC_p = n \ln(\text{SSE}) - n \ln(n) + 2p
\]

where \( n \) represents the sample size, \( p \) the number of parameters in the model, and \( \text{SSE} \) the error sum of squares (Akaike, 1974).

#### 2.3  Projecting future fossil and biomass RMC

The Shared Socioeconomic Pathway (SSP) framework is applied in the present study to project future fossil and biomass RMC. The SSP scenarios are a set of path dependent, alternative future projections up to the year 2100. They include population development, economic growth, and urbanization as key scenario drivers derived from qualitative narratives. The set consists of five basic scenarios and depicts key assumptions on future developments ranging from sustainable management of the global commons respecting environmental boundaries (SSP1) to the emergence of a globally integrated market- and technology-driven economy (SSP5) (Riahi et al., 2017). To develop the scenario drivers’ time series, future fertility, mortality, migration and educational transitions were projected depending on the assumptions prescribed by the SSP narratives. Subsequently, demographic scenarios along the dimensions age, sex, and level of education were estimated (KC & Lutz, 2017). The GDP projections were based on a macroeconomic production function with labor input, drawing on the demographic indicators (sex, age, and educational attainment level). Additionally, assumptions were made concerning physical capital investment, cross-sectional convergence, and technological progress.
TABLE 2  Country sample, categorized according to the SSP Public Database R5 regions

| SSP Public Database R5-Region                                                                 | Country code (ISO 3166 ALPHA-3) | Country name                                                                 |
|------------------------------------------------------------------------------------------------|----------------------------------|-------------------------------------------------------------------------------|
| Asian countries with the exception of the Middle East, Japan, and Former Soviet Union states  | CHN, IDN, IND, KOR               | China, Indonesia, India, South Korea                                         |
| Countries of Latin America and the Caribbean                                                  | BRA, MEX                         | Brazil, Mexico                                                                |
| OECD 90 and EU member states and candidates                                                   | AUS, AUT, BEL, BGR, CAN, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GB, GRC, HUN, IRL, ITA, JPN, LTU, LVA, NLD, POL, PRT, ROU, SVK, SVN, SWE, TUR, USA | Australia, Austria, Belgium, Bulgaria, Canada, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Hungary, Ireland, Italy, Japan, Lithuania, Latvia, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden, Turkey, USA |
| Countries from the reforming economies of Eastern Europe and the former Soviet Union          | RUS                              | Russia                                                                         |

(Crespo Cuaresma, 2017). The projected urban population was based on historical country-specific urban and rural growth rates (Jiang & O’Neill, 2017). In a second step, multiple integrated assessment models (IAM) were applied to estimate associated energy use, land cover, and greenhouse gas emissions for each scenario in a baseline variant as well as for various Representative Concentration Pathway (RCP) assumptions. Each RCP represents a reduction in greenhouse gas concentration caused by potential future mitigation policies. From the resulting scenario pool, so-called marker scenarios were selected which constitute an internally consistent and well-balanced subset in terms of the various IAMs applied (Riahi et al., 2017). The SSP projections data is available on IIASA’s SSP Public Database (IIASA, 2018).

In the present study, fossil and biomass RMCs were projected using the five SSP baseline marker scenarios assuming no future changes in greenhouse gas concentrations as a result of upcoming mitigation policies. (For detailed information on the SSP marker scenarios 1–5, see Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Van Vuuren et al., 2017; and Kriegler et al., 2017). For each of the RMC predictors we constructed a growth index from the SSP Public Database for the period 2010–2050 with 2010 as base year. This was applied to the 2010 historical data to arrive at extended time series up to 2050. For GDP, active population and urban population country-specific SSP projections were accessible in the database, while for the remaining predictors only regional aggregates were provided. In order to extend the production-based DMC predictor time series, we had to fall back on proxies, as no direct correspondences were available in the SSP Public Database. Fossil DMC changes were therefore approximated by the changes of region-specific fossil-based total primary energy supply (TPES) and biomass DMC changes by the changes of region-specific agricultural crop production in dry matter. Historically (1995–2008), logarithmized and within-transformed fossil DMC and fossil TPES were correlated with $r = 0.86$; biomass DMC and crop production with $r = 0.89$; and biomass DMC and crop production converted to dry matter with $r = 0.69$. Applying the selected best fixed effects (FE) models, we project fossil and biomass RMC.

3 | RESULTS AND DISCUSSION

The current section presents the results from panel fixed effects (FE) estimation for the sample countries as listed in Table 2 and discusses the current key driving and mitigating forces of fossil and biomass RMC. Next, we show RMC projections up to 2050 under adoption of the current drivers using the Shared Socioeconomic Pathways (SSP). FE estimation was conducted with linear as well as with log-transformed variables in different combinations. We found a general tendency for the log-transformed models to deliver slightly better results and therefore opted for log–log models, which is consistent with previous studies (Teixidó-Figueras et al., 2016; Wiedmann et al., 2015) and with theoretical considerations on the nature of driving forces behind anthropogenic environmental impacts (Ehrlich & Holdren, 1971).

3.1 | Driving forces of fossil and biomass RMC

Tables 3 and 4 present key statistics and the estimated coefficients of WIOD- and EORA-based fossil and biomass RMC models. We report on the results for drivers across the full sample of 37 countries as well as for a partial sample that excludes eight cases exhibiting disproportionate inconsistencies between WIOD and EORA in their mean fossil or biomass RMC values over time (AUS, BGR, CYP, EST, IRL, LVA, RUS, and SVK). Results are reported for full models including all predictors, and for best models, that is, those employing a relatively low number of predictors while maintaining a high goodness of fit. The adjusted $R^2$ lies between 0.45 and 0.67 for the full sample and between 0.45 and 0.61 for the partial
The urban population shows a negative association with both fossil and biomass RMC. The relationship is statistically significant in all models except for EORA-based biomass RMC. Multiple studies investigating a supposed positive association between the active population and national greenhouse gas emission or other ecological footprints report mixed results (Rosa & Dietz, 2012). Nonetheless, we find a negative relationship plausible, particularly under the consumption-based perspective of the present models. Given that the mean income of the active population is above the overall mean income, a decreasing active population share would diminish overall mean income. However, as we interpret the coefficient estimates under the ceteris paribus condition, GDP as a proxy for income is kept constant. In that case, a decline in active population implies increased mean incomes of the active and/or non-active population, which results in increased consumption. Thus, income availability negatively mediates between active population and RMC.

The urban population shows a negative association with both fossil and biomass RMC that is insignificant only in the case of EORA-based biomass RMC. The suggested tendency of upcoming urbanization to mitigate RMC is in line with recent findings in the literature (Weisz & Steinberger, 2010) showing that urban infrastructure may reduce direct material and energy requirements by virtue of economies of scale. At equal incomes, cities are found to be less energy intensive than rural areas. It does not appear unrealistic to expect further potential reduction due to infrastructure improvements. For example, in terms of embodied consumption, studies have shown below national average energy footprints for Australian cities (Lenzen, Wood, & Foran, 2008). This is supported by the fact that a reduction in direct energy and material use indicators leads to infrastructure improvements. However, as we interpret the coefficient estimates under the ceteris paribus condition, GDP as a proxy for income is kept constant. In that case, a decline in active population implies increased mean incomes of the active and/or non-active population, which results in increased consumption. Thus, income availability negatively mediates between active population and RMC.

The urban population shows a negative association with both fossil and biomass RMC that is insignificant only in the case of EORA-based biomass RMC. The suggested tendency of upcoming urbanization to mitigate RMC is in line with recent findings in the literature (Weisz & Steinberger, 2010) showing that urban infrastructure may reduce direct material and energy requirements by virtue of economies of scale. At equal incomes, cities are found to be less energy intensive than rural areas. It does not appear unrealistic to expect further potential reduction due to infrastructure improvements. For example, in terms of embodied consumption, studies have shown below national average energy footprints for Australian cities (Lenzen, Wood, & Foran, 2008). This is supported by the fact that a reduction in direct energy and material use indicators leads to a reduction in their consumption-based counterparts.

GDP is positively related to RMC throughout all models in the present sample. The elasticity of fossil RMC is higher than that of biomass RCM in both EORA- and WIOD-based models. Economic growth, affluence or final demand are recognized as key determinants of material use (e.g., Bithas & Kalimeris, 2017; Eisenmenger et al., 2016; Hatfield-Dodds et al., 2017; Krausmann et al., 2009; Pothen, 2017; Schaffartzik, Wiedenhofe, & Eisenmenger, 2015; Schandl & Turner, 2009; Shao, Schaffartzik, Mayer, & Krausmann, 2017; Wood, Lenzen, & Foran, 2009). Long-term material flow accounting studies have shown decreasing coupling intensities between GDP and direct material use as the economic development of countries proceeds. However, no evidence has been found for decoupling GDP and consumption-based material use (RMC) (Krausmann et al., 2017). On differentiating between various material use categories, a stronger elasticity has been found for fossil resources than for biomass, regardless of whether production- or consumption-based material uses were investigated (e.g., Steinberger et al., 2010; Wiedmann et al., 2015). This

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**TABLE 3** Full and best fixed effects (FE) models overview for fossil raw material consumption (RMC) (log–log). Best models were selected according to the Akaike information criterion (AIC)

| Response variable | Fossil RMC, 1995–2008 (14 years) |
|-------------------|-----------------------------------|
| Database          | EORA                              |
| Sample (N)        | Full (37)                          |
| FE model          | Full Best                          |
| FE model ID       | 1094 1823                         |
| GDP               | 0.64 0.64                         |
| Adjusted R²       | 0.60 0.60                         |
| AIC               | 2296 2297                         |
| Max VIF           | 2.16 2.11                         |
| Wald F test       | 118.41 137.75                     |
| R²                | 0.60 0.60                         |
| Adjusted R²       | 0.60 0.60                         |
| AIC               | 2296 2297                         |
| Max VIF           | 2.16 2.11                         |
| Wald F test       | 118.41 137.75                     |
| GDP               | 0.64 0.64                         |
| Adjusted R²       | 0.60 0.60                         |
| AIC               | 2296 2297                         |
| Max VIF           | 2.16 2.11                         |
| Wald F test       | 118.41 137.75                     |

Empty table cells indicate drivers that have been eliminated in the respective best model due to AIC-based model selection.

*p values < 0.01, < 0.05, < 0.10. All variables are normalized by population

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2 Variance inflation factors have been calculated including all observations, log-transformed, after within-transformation.
TABLE 4 Full and best fixed effects (FE) models overview for biomass raw material consumption (RMC) (log–log). Best models were selected according to the Akaike information criterion (AIC)

| Response variable | Biomass RMC, 1995–2008 (14 years) |
|-------------------|-----------------------------------|
|                   | EORA                              |
|                   | Full (37)                          |
|                   | Partial (29)                       |
|                   | FE model ID                        |
|                   | FE model Full Best Partial Full Best |
|                   | Database                            |
|                   | EORA WIOD                          |
|                   | Full Best Full Best                |
|                   | Sample (N)                         |
|                   | 1094 1178                          |
|                   | 1094 1337                          |
|                   | 1094 1176                          |
|                   | 1094 1418                          |
|                   | Estimates                           |
| Active population | −1.51*** −1.45*** −2.11*** −2.14*** |
| Urban population  | −0.14 −0.17 −0.20* −0.74*** −0.73*** |
| GDP               | 0.54*** 0.54*** 0.48*** 0.48*** |
| Pastures          | −0.04* −0.04** −0.10*** −0.03 |
| Forests/cropland  | −0.08 −0.23*** −0.23*** −0.06 |
| Fossil DMC        | −0.08** 0.10*** −0.03 −0.10** −0.11** |
| Biomass DMC       | 0.48*** 0.48*** 0.57*** 0.57*** |
| R²                | 0.69 0.69 0.65 0.65 |
| Adjusted R²       | 0.67 0.67 0.61 0.61 |
| AIC               | −2819 −2821 −2251 −2252 −2701 −2703 |
| Max VIF           | 2.16 2.07 2.23 1.96 |
| Wald F test       | 153.64 214.80 96.92 113.20 |

Empty table cells indicate drivers that have been eliminated in the respective best model due to AIC-based model selection. p values <0.01, <0.05, <0.10. All variables are normalized by population

The results for both pastures and forests/cropland are inconclusive. In EORA-based models, pastures are positively associated with fossil RMC and negatively associated with biomass RMC. In WIOD-based models, coefficients are mostly insignificant with the exception of a positive coupling with WIOD-based biomass RMC for the partial sample. Coefficient signs and significances of forests/cropland are mixed. The fossil EORA- and WIOD-based best models are contradictory regarding the impact direction of forests/cropland. Due to these inconsistencies, the predictors are not interpreted further.

There is a positive association between the DMC and RMC of the respective material (fossil or biomass resources). A one percent increase in DMC—which can be interpreted as growth of material production input to the domestic economy—raises the corresponding RMC by about half—a percent, that is, production-based material use variation is not fully reflected in RMC. Accordingly, DMC growth not only increases material embodied in domestic consumption but also in exports of manufactured products. Looking at temporal patterns, literature on material and energy intensity pathways reveals that high income countries have increasingly externalized their resource-intensive industries in recent decades (Dittrich et al., 2012; Krausmann et al., 2017 Wiedmann et al., 2015), indicating an ongoing trend of diminishing coupling between DMC and RMC. While DMC continues to be an important driver of RMC, the findings identify the presence of leakages with respect to production-based policy actions to promote the bioeconomy and highlight the need for flanking measures targeted at consumption.

3.2 Future fossil and biomass RMC

To link the regression results with the RMC projections for the present country sample, Table 5 presents the underlying assumptions of the SSP scenarios in condensed form in order to allow for a more substantial understanding of the causes of possible future changes in RMC driving forces. Based on the regression results, we then briefly describe how each driver affects the projected pathways of fossil and biomass RMC in the face of changing conditions.

For the sample consisting of mainly OECD countries, a reduction in the active population is expected due to population ageing in all SSP scenarios (change in overall mean value across countries from 68% in 2010 to 56–58% in 2050). Upcoming changes in demographic age structures are, therefore, ceteris paribus, likely to be accompanied by growth in RMC under the current configuration of RMC driving forces. The mitigation effect resulting from urbanization will be rather limited as expected urban population increase is only modest in all SSP scenarios (change in
TABLE 5 Overview of selected SSP scenario assumptions. Excerpt drawn from O’Neill et al. (2017). The World Bank income classification was used (low-income [LIC], medium-income [MIC], and high-income [HIC] countries)

| SSP element                  | SSP1                                                                 | SSP2                                                                 | SSP3                                                                 | SSP4                                                                 | SSP5                                                                 |
|------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Description                  | Sustainability—Taking the green road                                 | Middle of the road                                                  | Regional rivalry—A rocky road                                        | Inequality—A road divided                                            | Fossil-fueled development—Taking the highway                           |
| Population growth            | Relatively low                                                        | Medium                                                             | High                                                                | Low to relatively high                                               | Relatively low                                                        |
| Urbanization level           | High                                                                 | Medium                                                             | Low                                                                 | Med to high                                                         | High                                                                 |
| Growth (per capita)          | High in LICs, MICs; medium in HICs                                    | Medium, uneven                                                      | Slow                                                                | Low in LICs, medium in other countries                               | High                                                                 |
| Inequality                   | Reduced across and within countries                                   | Uneven moderate reductions across and within countries             | High, especially across countries                                    | High, especially within countries                                    | Strongly reduced, especially across countries                           |
| Consumption and diet         | Low growth in material consumption, low-meat diets, first in HICs     | Material-intensive consumption, medium meat consumption             | Material-intensive consumption                                       | Elites: high consumption lifestyles; rest: low consumption, low mobility | Materialism, status consumption, tourism, mobility, meat-rich diets    |
| Energy tech change           | Directed away from fossil fuels, toward efficiency and renewables    | Some investment in renewables but continued reliance on fossil fuels | Slow tech change, directed toward domestic energy sources           | Diversified investments including efficiency and low-carbon sources  | Directed toward fossil fuels; alternative sources not actively pursued |
| Fossil constraints           | Preferences shift away from fossil fuels                             | No reluctance to use unconventional resources                       | Unconventional resources for domestic supply                        | Anticipation of constraints drives up prices with high volatility     | None                                                                  |
| Land use                     | Strong regulations to avoid environmental tradeoffs                   | Medium regulations lead to slow decline in the rate of deforestation | Hardly any regulation; continued deforestation due to competition over land and rapid expansion of agriculture | Highly regulated in MICs, HICs; largely unmanaged in LICs leading to tropical deforestation | Medium regulations lead to slow decline in the rate of deforestation   |

overall mean value across countries from 72% in 2010 to 77–89% in 2050). Given the expected GDP growth for the country sample (change in overall mean value across countries from 29,108 $/cap in 2010 to 46,796–72,480 $/cap in 2050), GDP is the major driving force with the highest impact on projected RMC estimates and is therefore critical in any move toward a bioeconomic transition. In the study sample, a future reduction of forests/cropland is expected (change in overall mean value across countries from 1.53 ha/cap in 2010 to 1.23–1.48 ha/cap in 2050), which affects fossil RMC projections to a lesser extent. With respect to fossil DMC, approximated by fossil TPES, an increase is expected in SSP scenarios 2–5 e in overall mean value across countries from 3.94 t/cap in 2010 to 4.27–6.03 t/cap in 2050). In the SSP1 scenario (respective change to 3.04 t/cap), fossil DMC decreases. For biomass DMC, approximated by the agricultural crop production, SSP scenarios 1–4 show growth tendencies (change in overall mean value across countries from 3.59 t/cap in 2010 to 4.08–6.30 t/cap in 2050), while in the SSP5 scenario (respective change to 3.18 t/cap) biomass DMC declines. Subsequently, expected changes in fossil DMC will either lead to an increase in fossil RMC (SSP2–5), or contribute to a reduction in fossil RMC (SSP1), whereas anticipated changes in biomass DMC will enlarge (SSP1–4) or lessen (SSP5) future biomass RMC. Table 6 provides an overview of the multiplicative impacts of RMC drivers under each SSP scenario, reflecting changes between 2010 and 2050 based on mean values across countries.

To illustrate the impact of future socioeconomic developments as captured by the SSP framework, Figure 1 presents the summarized RMC projection results for the year 2050 under the assumption that the current driving forces continue. The median figure for the biomass RMC ranges between 9.63 and 12.59 t/cap in the EORA-based and 5.01 and 7.10 t/cap in the WIOD-based projections. With respect to fossil RMC, the median lies between 8.07 and 12.19 t/cap in the EORA-based and 12.22 and 23.50 t/cap in the WIOD-based projections.

SSP1, the sustainability scenario which supposes catch up growth in low and middle income countries, and medium growth in high income countries combined with low material consumption and a shift away from fossil resources (O’Neill et al., 2017), shows only marginally lower fossil RMC

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3 RMC projection time series of the 37 sample countries for all SSP scenarios are included in Supporting Information S1 and S2.
TABLE 6 Multiplicative impacts of drivers on RMC (mean values across countries, change between 2010 and 2050) under the SSP scenarios using best fixed effects (FE) models

| Response variable | Fossil RMC | Biomass RMC |
|------------------|-----------|-------------|
|                  | Database  | EORA        | WIOD        |
|                  | SSP1      | SSP2        | SSP3        | SSP4        | SSP5        | SSP1      | SSP2        | SSP3        | SSP4        | SSP5        |
| Active population| 1.27      | 1.23        | 1.20        | 1.21        | 1.26        | 1.87      | 1.72        | 1.62        | 1.65        | 1.84        |
| Urban population | 0.84      | 0.88        | 0.94        | 0.87        | 0.84        | 0.91      | 0.94        | 0.97        | 0.93        | 0.91        |
| GDP              | 1.96      | 1.88        | 1.50        | 1.80        | 2.17        | 1.78      | 1.72        | 1.41        | 1.66        | 1.95        |
| Pastures         | 0.97      | 0.99        | 1.00        | 0.99        | 0.97        | 1.00      | 1.00        | 1.00        | 1.00        | 1.00        |
| Forests/cropland | 0.97      | 0.97        | 0.99        | 0.99        | 0.94        | 1.08      | 1.07        | 1.02        | 1.03        | 1.16        |
| Fossil DMC       | 0.90      | 1.03        | 1.11        | 1.06        | 1.19        | 0.88      | 1.04        | 1.13        | 1.07        | 1.23        |
| Biomass DMC      | 1.00      | 1.00        | 1.00        | 1.00        | 1.00        | 1.00      | 1.00        | 1.00        | 1.00        | 1.00        |

in the EORA-based projections than in other scenarios. In WIOD-based fossil RMC pathways, the sustainability assumptions do not lead to a clear reduction in fossil and biomass RMC compared to other scenarios (e.g., SSP2). The lowest inter-scenario fossil RMC values in WIOD projections are realized under the regional rivalry assumptions of SSP3 with slow growth, slow technological change, and high inequality on the one hand, and material-intensive consumption on the other hand (O’Neill et al., 2017). SSP2 and SSP4, the middle of the road and inequality scenarios, assume low to medium growth as well as moderately reduced to high inequality. Consumption in SSP2 is generally material-intensive while under SSP4, consumption levels between elites and non-elites are highly segregated (O’Neill et al., 2017). In the EORA-based projections, these assumptions lead to similar results, slightly above those of SSP1 and SSP3, while under WIOD a larger relative distance to SSP3 is shown. SSP5 postulates high growth, strongly reduced inequality, materialist status consumption, and meat-rich diets facilitated by fossil resources (O’Neill et al., 2017). Unsurprisingly, fossil RMC outcomes under SSP5 are noticeably higher than in other scenarios while biomass RMC is only marginally lower.

The question of how individual countries might be affected under the various SSP scenarios can be addressed by looking at RMC convergence patterns. Crespo Cuaresma (2017) has demonstrated the usefulness of beta-convergence plots to study income convergence. We apply the concept to show, how the SSP scenarios differ in terms of RMC convergence across countries. The panels in Figure 2 present, for each country, the projected log-transformed RMC growth between 2010 and 2050 against the corresponding 2010 log-transformed RMC level under the various SSP scenarios. A negative correlation between growth and level signifies convergence, for example, countries with comparably low recent RMC levels tend to grow their RMC more strongly. SSP1–3 present convergence tendencies without significant differences in slopes in most cases; as an exception, convergence of WIOD-based fossil RMC is stronger under the regional rivalry assumptions of SSP3 than under other scenarios, which is not the case for EORA-based fossil RMC. The inequality assumptions of SSP4 lead to the least pronounced RMC convergence trends across both material types and databases; for biomass RMC, insignificant convergence (EORA-based) or even divergence (WIOD-based) patterns may be expected under SSP4. Of all scenarios, SSP5 shows the strongest convergence tendency for biomass RMCs, that is, countries with previously below-average biomass RMC levels will catch up under a fossil-fueled development. With respect to fossil RMC, convergence is comparably strong (EORA-based) or below-average (WIOD-based).

The tendency of most SSP scenarios to converge RMCs does not mean; however, an absolute reduction in countries with previously above-average RMC levels, but rather an absolute increase in countries with low initial RMC values. Of all 370 fossil RMC pathways, only one absolutely declines in the period of 2010–2050 (EORA-based fossil RMC of Slovenia in SSP1, see Figure S1-1 in Supporting Information S1, SVN under SSP1). Of the 370 biomass RMC paths, 11 exhibit a minor decrease.4 Under the SSP scenarios considered, the continuation of the current RMC driving

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4 Decreasing biomass RMC paths are shown in Figure S1-1 in Supporting Information S1, WIOD-based biomass RMC under SSP1 and 5 (SVK, SVN); SSP3 and 4 (KOR); and SSP5 (AUT, CZE, DEU, IRL, JPN).
forces leads to an absolute increase of fossil and biomass RMC. This finding is reflected in both EORA- and WIOD-based projections, notwithstanding the differences in their construction principles, data sources, and partial inconsistencies in RMC estimates. The expectation of fossil RMC growth in spite of enlarging biomass RMCs contradicts a number of frequently mentioned objectives in bioeconomy strategies, such as reducing fossil resource dependency, mitigating climate change, or improving energy security (see Priefer et al., 2017). The main reasons for the anticipated increase in fossil RMC, and thus the main factors hindering any effective move toward a bioeconomic transition, are the positive coupling of fossil...
FIGURE 2 Per capita fossil and biomass raw material consumption (RMC) projections (annual t/cap), log-transformed RMC growth (2010–2050) against 2010 log-transformed RMC level under SSP1–5 (rows). (a) Biomass RMC projection based on EORA; (b) biomass RMC (WIOD); (c) fossil RMC (EORA); (d) fossil RMC (WIOD). Underlying data used to create this figure can be found in Supporting Information S2.
RMC with GDP and the negative coupling with the economically active share of the population. As discussed previously, both of these drivers are directly or indirectly attributable to income availability and associated consumption levels.

4 | CONCLUSIONS

The present paper has provided an estimate of fossil and biomass raw material consumption (RMC) for a number of countries using environmentally extended multiregional input–output analysis (EEMRIO). The current key driving and mitigating forces of fossil and biomass RMC were identified by means of panel fixed effects (FE) models. Assuming the continuation of current driving forces, and using the Shared Socioeconomic Pathways (SSP) framework, it proved possible to arrive at projections for future fossil and biomass RMC. A comparison between EORA- and WIOD-based projections indicates that our results are consistent in terms of direction, but differ in terms of magnitudes. Several factors tend to undermine any effort at precise estimation of magnitudes. For example, WIOD does not have a dedicated fossil resources extractive sector. This could thus lead to biased fossil RMC estimates. We also had to use proxies for fossil and biomass domestic material consumption (DMC) in the RMC projections as this data is not provided in the Public SSP database. The present analysis does not take all constraints into account, for example, the potential for systemic disruption should conflicts intensify between resource use and ecosystem health. Furthermore, including additional explanatory variables could improve the goodness of fit of the FE models. For all the above reasons, the projection results presented here should be interpreted cautiously, and taken as a depiction of a general trend rather than as country-specific estimates of future RMC levels. However, the lack of ambiguity with respect to the tendency for increasing fossil and biomass RMCs across most countries and SSP scenarios, in both EORA and WIOD-based projections, lends support to the view that the results are sufficiently robust to support our conclusions.

Assuming that the strong coupling between income, as approximated by GDP, and fossil RMC continues, we conclude that upcoming socioeconomic conditions lead to an increase—instead of a decrease—of fossil raw material consumption (RMC) under all scenario assumptions. A shift in RMC from fossil resources to biomass would require a decoupling of GDP and fossil RMC by recoupling GDP with biomass RMC. This serves to underline the argument that mere growth in biomass use will not necessarily lead to reduced fossil resource consumption. Given the central nature of scarcity issues with respect to biomass, land, and water, it would appear that a much greater effort needs to be made in assessing the relevance of technological bio-based innovations for the reconfiguration of RMC drivers on a macro level.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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