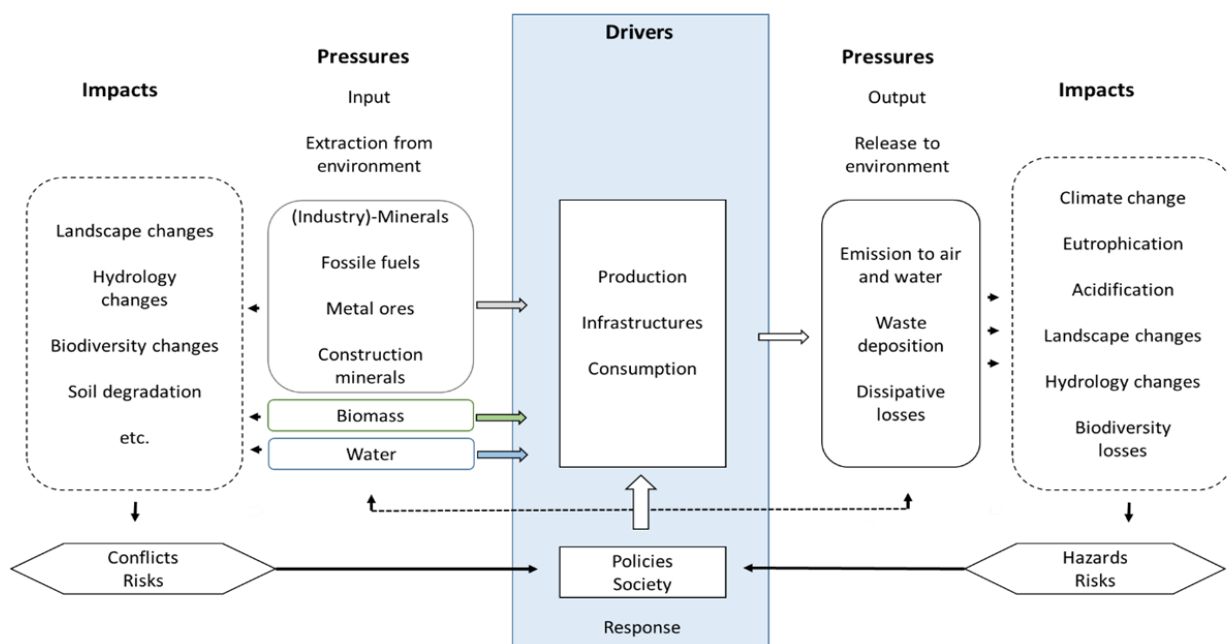


## Supplementary Information

### Conceptualization of an indicator system for assessing the sustainability of the bioeconomy

Vincent Egenolf and Stefan Bringezu

**Figure S1: DPSIR System - Schematic interdependency of resource use and environmental impacts, (adapted and amended from Bringezu et al. [1])**



**Table S1: Overview of resource footprint concepts and authors in the current scientific literature**

| Footprint  | Authors | Definition   | Unit  |
|--|---------|--|---|
| Ecological Footprint<br>( <i>not included in the article</i> ) | [2–4]   | The ecological footprint describes the anthropogenic load on the planet in the form of a combination of real and virtual land use. The concept is dominated by the inclusion of land and ocean areas theoretically required for CO <sub>2</sub> uptake in biomass.   | Global hectare [gHa]  |
| Material footprint   | [5–7]   | The material footprint of domestic consumption (Raw Material Consumption [RMC]) is calculated from the total domestic extraction of raw materials and the quantity of raw materials used abroad for the production and processing of products, which is indirectly used by domestic consumers through the import of these products. The quantity of raw materials used for domestic export products, which is indirectly used by consumers abroad, is deducted from this amount. If this subtraction is omitted, the material footprint of domestic production is obtained.                | [kg/process],<br>[kg/product],<br>[kg/person]   |
| Agricultural land footprint                                    | [1,8]   | The agricultural land footprint is calculated from the amount of land under cultivation in Germany and the amount of land under cultivation abroad which is indirectly used for domestic consumption via the import of products. This is the footprint of domestic production. If the amount of arable land for export products is deducted, the arable footprint of domestic consumption results.   | [ha/process],<br>[ha/product],<br>[ha/person]   |
| Forest footprint   | [9]     | The forest footprint of domestic consumption is calculated from the total domestic harvest of primary timber and the amount of primary timber used abroad for the production and processing of products, which is indirectly used by domestic consumers through the import of these products. The amount of primary timber used for domestic export products, which is indirectly used by consumers abroad, is deducted from this amount. If this subtraction is omitted, the forest footprint of domestic production is obtained.   | [m <sup>3</sup> / process],<br>[m <sup>3</sup> / product],<br>[m <sup>3</sup> / person]                   |
| Water footprint  | [10–12] | The blue water footprint refers to the amount of surface water and/or groundwater consumed by a person or group of persons, a product or a process.<br>The green water footprint is composed of the quantities of precipitation water released into the atmosphere by evapotranspiration of the plant and evaporation of the soil during the growing period (or lifetime) of a crop. The footprint indicators of production and consumption are calculated analogously to the above footprints.  | [m <sup>3</sup> / process],<br>[m <sup>3</sup> / product],<br>[m <sup>3</sup> / person]                   |
| Carbon footprint<br>(here climate footprint)                   | [13]    | The climate footprint cumulates the direct and indirect greenhouse gas emissions of all processes associated with a product or service over the entire life cycle of a product or service. For a country, it usually accounted for on a yearly basis. "Indirect greenhouse gas emissions" refer to the emissions that must be allocated to the region of consumption via the import/export of products from the region of production and processing or the like. The climate footprint of domestic production and consumption is calculated analogously to the footprints described above. | [kg CO <sub>2</sub> -eq/process],<br>[kg CO <sub>2</sub> -eq/product],<br>[kg CO <sub>2</sub> -eq/person] |

**Table S2: Key objectives, criteria and indicators of social sustainability**

The relevant key objectives of social sustainability are listed in Table S2. Criteria are assigned to the key objectives, which in turn are quantified by indicators. The last column of the table shows the scaling level and possible data sources. Criteria that are also explicitly mentioned in the subject catalogue of the SDGs are listed separately, stating the respective number. Aspects marked with an asterisk (\*) were classified as particularly relevant in the stakeholder analysis reported of Zeug et al. [14]. Indicators marked with (") are not part of regular data collection, but refer to the results of individual reports. Criteria of social sustainability are based on company and employment statistics. The survey method is often empirical research.

| Key objectives         | Criteria                         | SDG      | Indicators  | Scale level/ Source                        |
|------------------------|----------------------------------|----------|---|--|
| Education and Training | Education                        | 4.3      | Number and rate of in-company trainees  | national [15], EU [16]                     |
|                        | Training                         | 4.3      | Number of employed persons who have participated in occupation-related non-formal training/further training in the last 12 months | national [15], EU [16]                     |
| Working conditions     | Work safety                      | 8.8      | Number of Accidents and fatalities at work  | national [15], EU [16], international [17] |
|                        | International working conditions | 8.7      | Child labor/ forced labor   | national [15], international [18]          |
|                        |                                  | 8.8      | Average number of hours worked per week   | national [15], EU [16] international [17]  |
| Social integration     | Gender                           | 5.5      | Number of female/ transgender employees   | national [15], EU [16] international [17]  |
|                        |                                  | 5.a, 8.5 | Gender specific earnings gap  | national [15], EU [16] international [17]  |
|                        | Inclusion                        | 4.a      | Proportion of employees with disabilities   | national [15], EU [16] international [17]  |
|                        | Integration                      | 10.7     | Proportion of employees with a migrant background   | national [15], EU [16]                     |
| Workers' rights        | Trade union organization         | 8.8      | Number of employees with collective labor agreement   | national [15], EU [16] international [19]  |
|                        |                                  |          | Number of employees in trade unions   | national [15], EU [16] international [19]  |

|                         |                         |             |  |                    |
|-------------------------|-------------------------|-------------|--|--------------------|
| Cooperation orientation | Stakeholder involvement |             | Involvement of stakeholders in strategy development and planning (qualitative)"      |                    |
|                         | Project cooperation     |             | Cooperation in the context of PPP projects, research projects and NGOs (qualitative) | national [20]      |
|                         |                         |             | Patent protection aspects (qualitative)  | national [21]      |
|                         |                         |             | Access to knowledge (qualitative)"   | national [22]      |
| Legal certainty         | Land rights             | 1.4,<br>5.a | Establishment and implementation of land rights in the legal system (qualitative)    | international [23] |

**Table S3: Key objectives, criteria and indicators of economic sustainability**

Criteria and indicators are assigned to the four key objectives of economic sustainability (Table S3). The last column of the table shows the scaling level and possible data sources. Criteria that are also explicitly mentioned in the subject catalogue of the SDGs are listed separately, stating the respective number. Aspects marked with an asterisk (\*) were classified as particularly relevant in the stakeholder analysis reported of Zeug et al. [14]. The indicators of economic sustainability are largely based on company and employment statistics and are recorded by statistical surveys. Indicators marked (") are not part of regular data collection but refer to the results of individual reports.

| Key objective   | Criteria              | SDG           | Indicators                                  | Scale level / Source                                    |
|-----------------|-----------------------|---------------|---|---|
| Employment      | Employment conditions | (9.5),<br>8.5 | Number of employees in FTE                  | national/ [15]<br>EU/ [16]<br>international/ [19], [24] |
|                 |                       |               | Number of fixed-term employees              | national/ [15]<br>EU/ [16]                              |
|                 |                       |               | Number of informal employment relationships | International / [17]                                    |
|                 | Qualification         |               | Number of employees by qualification        | national/ [15]<br>EU/ [16]<br>international [17]        |
|                 | Living Wage           | 1.2           | Number of employees below the living wage   | EU/ [16]<br>international [17]                          |
|                 | Income                | 8.5,<br>10.1  | Average monthly income                      | national/ [15]<br>EU/ [16]<br>international [17]        |
|                 | Income Gap            | 10.2          | Gini-Coefficient                            | national/ [15]<br>EU/ [16]<br>International [25]        |
| Competitiveness | Product-related       |               | Global Competitiveness Index                | international [19]                                      |
|                 | Personnel-related     |               | Global Competitiveness Index                | international [19]                                      |

|             |                           |     |   |  |
|-------------|---------------------------|-----|---|--|
| Value added | Gross-/ Net value added   | 8.2 | Added value of the selected bioeconomy sectors  | national/ [15]<br>EU/ [16]<br>International [19] |
| Innovation  | Social innovation         |     | Share of turnover of companies in the eco- and environmental service branch in the total turnover | International [26]                               |
|             | Process innovation        | 9.b | Number of ISO 14001 registered companies  | international [26]                               |
|             | Product innovation        | 9.b | Number of patents related to eco-innovations  | international [26]                               |
|             | Promotion of SMEs         | 9.3 | Number of research and development projects funded in SMEs".                                      | national [27]                                    |
|             | Access to capital by SMEs | 9.3 | Maximum eligible costs"   | national [27]                                    |

**Table S4: Key objectives, criteria and indicators of environmental sustainability**

The pillar of environmental sustainability refers to the basis of human life (Table S4). The overriding goal is to reduce the influence of human activities that adversely affect these livelihoods to an acceptable level. The biophysical assumptions on which the indicators of ecological sustainability are based come from various data sources such as the FAOSTAT database. The last column of the table shows the scaling level and possible data sources. Criteria that are also explicitly mentioned in the subject catalogue of the SDGs are listed separately, stating the respective number. Aspects marked with an asterisk (\*) were classified as particularly relevant in the stakeholder analysis reported of Zeug et al. [14]. Indicators marked with (") are not part of regular data collection, but refer to the results of individual reports.

| Key objectives                              | Criteria   | SDG     | Indicators  | Scale level / Source                                |
|---|--|---------|---|---|
| Contribution to climate protection          | Emission of greenhouse gases                           | 13, 9.4 | Amount and type of ghg emissions  | national [15]<br>EU/ [16]<br>international/ [28,29] |
|   | Carbon storage   |         | Amount of carbon stored in grassland and forest area                            | national/ [30]<br>international/ [31]               |
| Preservation and improvement of air quality | Gaseous pollutant emissions to atmosphere (beside GHG) |         | Total emission by type of pollutant   | international/ [25]                                 |
|   | Particulate matter                                     | 11.6    | Particulate matter emissions PM <sub>2,5</sub>                                  | national [15]<br>EU/ [16]<br>international/ [32]    |
| Preservation of water balance and -quality  | Water quality  | 6.3     | Phosphorus load [and nitrate influx <sup>1</sup> ] in ground- and surface-water | national/ [33]<br>EU/[33]<br>international/ [33]    |
|   | Water quantity   | 6.4     | Extraction of ground- and surface-water   | national/ [33]<br>EU/ [33]<br>international/ [33]   |
|   |  |         | Water- scarcity-index (WSI)   | national/ [33]<br>EU/ [33]<br>international/ [33]   |

<sup>1</sup> [not yet implemented in WaterGAP]

|   |                            |       |  |                     |
|---|----------------------------|-------|--|---------------------|
| Preservation and strengthening of biodiversity* | Biodiversity of ecosystems | 14,   | Diversity as the presence of indicator species     | international/ [34] |
|   |                            | 15.5  | Proportion of invasive species in total diversity  | international/ [34] |
|   | Agrobiodiversity           | 2.4   | Diversity of crops used                            | international/ [35] |
|   |                            |       | Number of genetically modified organisms           | International/ [36] |
|   | Habitats                   | 14.5, | Share of grassland in cultivated agricultural land | international/ [37] |
|   |                            | 15.1  | Protected area as a percentage of the total area   | international/ [37] |
| Preservation of soil fertility and function *   | Use of agrochemicals       |       | Type and quantity of chemical used                 | International/ [38] |
|   | Soil fertility             |       | Share of organic carbon content                    | International/ [38] |
|   | Soil structure             |       | Dry bulk density                                   | International/ [38] |
|   | Erosion                    | 15.3  | Average annual amount of soil erosion              | International/ [38] |



**Table S5: FAO - Food Security Indicators [39]**

|   |
|---|
| FOOD SECURITY INDICATORS  |
| AVAILABILITY  |
| Average dietary energy supply adequacy                                |
| Average value of food production                                      |
| Share of dietary energy supply derived from cereals, roots and tubers |
| Average protein supply  |
| Average supply of protein of animal origin                            |
| ACCESS  |
| Rail lines density  |
| Gross domestic product per capita (in purchasing power equivalent)    |
| Prevalence of undernourishment  |
| Prevalence of severe food insecurity in the total population          |
| Depth of the food deficit   |
| STABILITY   |
| Cereal import dependency ratio  |
| Percent of arable land equipped for irrigation                        |
| Value of food imports over total merchandise exports                  |
| Political stability and absence of violence/terrorism                 |
| Per capita food production variability                                |
| Per capita food supply variability                                    |
| UTILIZATION   |
| Access to improved water sources                                      |
| Access to improved sanitation facilities                              |
| Percentage of children under 5 years of age affected by wasting       |
| Percentage of children under 5 years of age who are stunted           |
| Percentage of children under 5 years of age who are overweight        |
| Prevalence of obesity in the adult population (18 years and older)    |
| Prevalence of anemia among women of reproductive age (15-49 years)    |
| Prevalence of exclusive breastfeeding among infants 0-5 months of age |
| ADDITIONAL USEFUL STATISTICS  |
| Total population  |
| Number of people undernourished                                       |
| Number of severely food insecure people                               |
| Minimum Dietary Energy Requirement (MDER)                             |
| Average Dietary Energy Requirement (ADER)                             |
| Coefficient of variation of habitual caloric consumption distribution |
| Skewness of habitual caloric consumption distribution                 |
| Incidence of caloric losses at retail distribution level              |
| Dietary Energy Supply (DES)   |
| Average fat supply  |

**Table S6: Reference values of sustainable resource use** (amended and supplemented from O'Brien et al. [40])

|                               | Materials   | Agricultural Land  | Carbon   | Water   | Primary timber  |
|-------------------------------|---|--|--|---|---|
| Target orientation            | 10 t TMC <sub>abiotic</sub> /person <sup>2a</sup>   | 0,20 ha cropland/person <sup>b</sup>   | 1,05 t/person <sup>c</sup>   | 110-450 m <sup>3</sup> water use/person   | 0,4 m <sup>3</sup> [EU: 1,25 m <sup>3</sup> ] primary timber/person   |
| Impact on EU citizens by 2050 | ca. 70 % reduction compared to 2008   | ca. 45 % reduction compared to 2007  | ca. 90 % reduction compared to 2010  | ca. 30-50 % reduction compared to 2004 <sup>e</sup>   | ca. 26% reduction compared to 2010  |
| Source                        | [41]  | [1,42]   | [43,44]  | [43,45,46]  | [9]   |
| Rationale                     | Return to a global level of mineral extraction equivalent to the year 2000 (without considering erosion)<br>Calculation | Halt the loss of biodiversity and keep land use change (LUC) within the safe operating space           | Keep global warming within 2 degrees Celsius (67% probability)   | Scenarios based on potential efficiency improvements and demand-side reductions under four "One Planet" scenarios     | Keep primary timber use within the safe operating space   |
| Calculation                   | Global total mineral extraction in the year 2000 divided by expected world population in 2050                           | Max cropland area of 1.6 Mha divided by expected world population in 2030                              | Global cumulative cap of 750 GtCO <sub>2</sub> [47]; budget of 9.6GtCO <sub>2</sub> in 2050 divided by expected world population in 2050 | Limit of the global use of blue water after [45] divided by the expected world population in 2050                     | Limit of the global use of primary timber in 2050 divided by the expected world population in 2050                          |
| Research needs                | Link global resource extraction to social acceptance of impacts (e.g. as criticality and pollution)                     | Develop targets for forests and pastures; better understand potentials for winning back abandoned land | Expand the target beyond the CO <sub>2</sub> portion of the carbon footprint   | Quantify a global target or explore possibility of regional targets that may be linked to global safe operating space | Improve the data situation (in particular for the sustainable extraction of forest residues), develop more robust scenarios |

<sup>2</sup> 5 t RMC<sub>abiotic</sub>/Person [48]

<sup>a</sup> The original footnote has no relevance for bioeconomy in this form and is therefore not shown.

<sup>b</sup> Target refers to the base year of 2030; continued population growth and expansion of built-up land would further reduce the target, whereas land restoration (e.g. of abandoned land) could mitigate some of these effects. The timeframe of 2050 is too far to anticipate such trends; instead 0.2 ha is proposed as a clear, easy-to-communicate and directionally safe target

<sup>c</sup> Study presents as a carbon footprint “benchmark” and not as a target per se.

<sup>d</sup> This range depicts the potential footprint savings in society for different transition pathways in the EU, but does not reflect a sustainability benchmark based on what may be considered a sustainable level of resource use (in other words a boundary „defined“ by the natural conditions)

<sup>e</sup> Note that this reflects the scale of the challenge until 2050 to be consistent with the ranges presented for the other targets. It thus assumes continued population growth until 2050 and a reduced per capita availability of cropland (e.g. around 0.17 ha) and is for indicative purposes only (see note iv above)

<sup>f</sup> Based on data provided in the EoraMRIO Database and calculated by the authors<sup>3</sup>.

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<sup>3</sup> <http://www.worldmrio.com/>

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