Shifting Hazards: Footprint trends of the German Bioeconomy

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Abstract

Hoping to support sustainability, many countries established policies to foster bioeconomy (BE). While shifting towards more biomass use bears chances and risks, appropriate monitoring is still lacking. Here we show for the first time global key environmental footprints (FPs) of the German BE. From 2000 to 2030, the agricultural biomass FP is dominated by animal-based food consumption, which is slightly declining. Forest biomass FP of consumption could be potentially supplied from domestic territory. Agricultural land use for consumption is triple of domestic agricultural land (which covers half of Germany), having induced significant land use change in other regions from 2000 to 2015. Water FP for irrigation has decreased and might decline in absolute terms, but the share of supply regions with water stress might increase until 2030. The climate FP of BE contributes 20 to 18 % to the total climate FP of domestic consumption, while employment makes up 10 % and value added only 8 % of total.

Introduction

Still, many believe in a basic misconception: biomass is renewable and its use would generally be sustainable. In the past decades, several countries like USA, Sweden and Germany, as well as the European Union and the OECD have established policies to foster a shift towards a bioeconomy (BE)^{1,2}. The intention was mainly to substitute fossil and mineral-based resources by biomass, and there have been high hopes in additional income of farmers and foresters through bioenergy and biomaterials, sustaining rural development, and economic growth through innovations in biotechnology³. As a consequence of increased use of biomass, however, unwanted side-effects turned out, such as land use change, directly or indirectly induced by growing demand for both food, fibres and fuels, leading to an overexploitation of biotic resources, water and land domestically and internationally^{4,5} losses of biodiversity⁶ and to an overcompensation of GHG savings by biofuels⁷. It has become clear, meanwhile, that any BE would only be sustainable when following important principles⁸, and when balanced against critical thresholds of global sustainable resource use^{9,10}. BE strategies are now being directed towards a more circular economy with higher resource efficiency^{11,12}.

While policy strategies have been implemented and billion dollar heavy industries such as on biofuels have been created, a comprehensive monitoring of the actual performance of BE regarding the achievement of sustainability goals, including the effects of past and ongoing policies has been largely lacking^{13,14}. Requirements and concepts for bio-economy monitoring are discussed for example by O'Brien et al.¹⁵ and Robert et al.¹⁶. In this context resource FPs are seen as suitable indicators to assess the environmental effects of human consumption (e.g. Tukker et al.¹⁷).

In this article, we provide for the first time a comprehensive analysis of past and projected resource and climate FPs of the German BE and relate them to its socio-economic

performance. Building on conceptual^{15,18} and empirical^{17,19} work, we concentrate on the material (forest and agricultural biomass), agricultural land, water and climate FPs as an essential part of a future monitoring system. FPs were calculated for the historic period from 2000 – 2015 and for a trend projection until the year 2030.

Findings

The environmental FPs of the German BE have been determined on the basis of global, life-cycle-wide requirements of fully or partly biomass-based products annually produced and consumed in Germany, for *agricultural raw materials (agriculture biomass FP)*, *primary timber (forestry biomass FP)*, *agricultural land (land FP)*, *irrigation water (water FP)*, and *greenhouse gas (GHG) emissions (climate FP)*. The FPs of the German BE account for the global pressures of total *supply, comprising domestic production plus imports*; those of exports are deducted when measuring *FPs of domestic consumption*. The environmental FPs are complemented by socio-economic indicators of value added and employment.

Agricultural biomass footprint

In 2015, Germany harvested 214 Mt of agricultural biomass on own territory. The trade balance for directly traded agricultural products revealed an import dependency (31 Mt imports vs. 19 Mt. exports). Considering the FPs of imports and exports, that dependency becomes more pronounced, with direct and indirect flows of biomass accounting 311 Mt for imports vs. 110 Mt for exports. One reason for these massive differences in magnitude is that fodder crops and crop residues are seldom directly traded but indirectly in form of the products made from the fed animals.

In 2015, the agricultural biomass FP of consumption amounted to 5.0 t/person and exceeded the global average of 2.8 t/person by 81 % (Figure 1a). When ongoing trends of shifts in

71 dietary patterns like a slightly decreasing meat consumption in Germany are projected to
72 continue to 2030 the exceedance may decrease to below 50 %.

73 Globally about 40 % of harvested agricultural biomass is used in the form of grains or other
74 primary crops, while 60 % is being grazed or used as crop residues, fodder or energy crops.
75 This predominance of biomass for feed (and energy) purposes upon biomass for food (and
76 clothing) purposes can also be observed for Germany's agricultural biomass FP with a share
77 of grains and other primary crops of 43 to 45 % in the reporting period. Cereal grains
78 contribute one third to the primary crops used, and about 60 % of the cereals produced or
79 imported are being used as feed²⁰. Thus, the major part of harvested agricultural biomass is
80 used for animal production.

81 *Forestry biomass footprint*

82 Germany is a net importer of roundwood equivalents (RE) (Fig. 1b). The forest FP of
83 domestic consumption exceeded domestic roundwood production by about 45 % on average
84 from 2000 to 2015. The past level of the consumption FP of 95.1 Mm³ RE on average could
85 have been completely supplied from domestic territory as it lay within the bandwidth which
86 outlined the potential of sustainable national roundwood production ranging from 86 to 114
87 Mm³ RE in 2015 to 79 to 118 Mm³ RE in 2030²¹. For exports, ongoing trends would lead to
88 rising volumes up to 32 Mm³ RE until 2030. Then, the total demand for RE for the domestic
89 production would reach a level which could no longer be supplied from own territory only.

90 The average German consumption of RE has been 1.17 ± 0.06 m³/person, thus not exceeding
91 1.25 m³/person, a value which had been proposed for safe and just maximum roundwood
92 consumption considering the productivity of European forests²². Globally, the average
93 consumption of RE is significantly lower than Germany's (Fig. 1b) as many regions are void

of forests and use other materials instead. Thus, with regard to availability and productivity, a comparison seems more adequate with European forests.

Land footprint

Germany uses triple of domestic agricultural land globally to supply its consumption. In 2015, the land FP was 51 Mha, compared to 17 Mha of domestic agricultural area. The land FP might decrease in the coming years, if ongoing trends of reduced meat consumption were to continue (Fig. 1c). German land FP of consumption would fall below global per person average; however, cropland use – which is the most intensive form of agricultural land use – might still be beyond average in 2030 (Fig. 2a), and would also exceed the 0.20 ha/person which had been suggested as proxy safe operating space²³.

The increased biomass consumption in Germany in the early 2000s had not only led to land use per person above global average. It significantly contributed also to land transformation, primarily in other regions of the world (Fig. 2b). Whereas global average annual transformation rate between 2000 and 2015 fluctuated between 19 to 22 m²/person (Fig. 2c), the German induced foreign land use change per year started with 90 m²/person in the period 2000-2005, decreased to 32 m²/person in 2015 and might go down to zero until 2030. This indicates that Germany had exerted its major pressure towards global land use change and loss of natural habitats due to its increases in biomass demand - which was higher than yield increases - in past decades. From 2000 to 2005 mainly forest was converted to agricultural land, while from 2010 onward mainly used grassland was transformed for more intensive uses. Land conversion and intensification might have been associated with loss of biodiversity.

Projection data on future development are uncertain, not only because of the not yet considered Covid-19 impact, but also due to variation of yield increase, assumptions on

development of built-up land and rewetting of fields on former peatland, and varying substitution of imports by domestic production. As consequence, in 2030, land FP of German BE production could range +/- 14 to 15 % around a medium 45 Mha. Medium Land FP of consumption would be 37.6 Mha and range -12 % to +15 % (Table 1).

	Agricultural land footprint			Water footprint		
	Of			of		
	Consumption	Exports	Supply	Consumption	Exports	Supply
	(Mha)			(km ³)		
Maximum	43.1	18.6	51.8	15.1	3.6	18.7
Medium	37.6	16.7	45.0	11.5	2.8	14.3
Minimum	33.1	15.4	38.7	5.4	1.3	6.7
Range	-12 % to + 15%	-8 % to +11 %	-14 % to +15 %	-53 % to +32 %	-54 % to +28 %	-53 % to +31 %

Table 1. Variation of agricultural land footprint and water footprint projected for 2030 for domestic consumption, export, and total supply (domestic production plus imports). Medium: projection of current trends. Minimum: compared to ongoing trend +20 % higher yield increases; -20 % lower rate for new built-up areas; -34 % lower rate for rewetting of organic soils. Maximum: compared to ongoing trends -20 % lower yield increases; +20 % higher rate for new built-up areas; +34 % higher rate for rewetting of organic soils.

130 *Water footprint*

131 The water FP for domestic consumption of agricultural goods comprises annual irrigation
132 water withdrawals, mainly in foreign regions (98 %). While ongoing trends indicate that, as a
133 consequence of climate change, global irrigation water withdrawals might grow by up to 21 %
134 from 2015 to 2030, the German water FP is expected to decline by 28 % (from 15.8 km³ to
135 11.5 km³) mainly due to changing import structure. On a per-person basis, global irrigation
136 water withdrawals might slightly decline from 2015 to 2030 from 263 to 226 m³/person, while
137 the German water FP will decrease from 192 m³/person to 138 m³/person) (Fig. 1d).

138 Varying material flows of different primary crops both unprocessed and embedded in
139 consumed products have led to changes in the composition of the water FP (Fig. 3). In 2000,
140 the water FP attributable to the consumption of products based on cotton made up for 31 % of
141 the total water FP, followed by wheat (22 %), paddy rice (13 %), and vegetables/fruits/nuts
142 (11 %). By 2015, the share of cotton was halved (14 %), while the contribution of
143 vegetables/fruits/nuts doubled (22 %). Contributions by remaining crops show comparably
144 small variations in relative terms. In absolute terms, the reduction of the water FP from 20.4
145 km³ in 2000 to 15.8 km³ in 2015 equals roughly the decline in the water FP of cotton-based
146 products (4.1 km³). By 2030, paddy rice is projected to contribute most to the water FP
147 (24 %), followed by vegetables/fruits/nuts (23 %), wheat (17 %), and cotton (10 %).

148 Global irrigation water withdrawals afflicted with water stress per person are found to
149 decrease from 125 m³ to 101 m³ (-19 %) between 2000 and 2030. The part of the German
150 water FP stemming from water-stressed regions might decrease from 96 m³/person to 60
151 m³/person (-37 %) in the same period. Hence, the pressure on water resources per person
152 induced by Germany's consumption of embodied irrigation water is less than the global
153 average and is projected to decline.

The source regions of three quarters of the water FP afflicted with water stress in 2015 are located in the Middle East (35 %), Central and South-East Asia (25 %), and China (16 %). In these regions, up to 2 % of their total irrigation water withdrawals from regions with high water stress are attributable to Germany's consumption.

In the Middle East, irrigation of vegetables/fruits/nuts (52 %), wheat (17 %), and oil seeds (10 %) contributes most to the water FP afflicted with water stress. Large parts of the Middle East suffer from high water stress, resulting in 61 % of water withdrawals for vegetables/fruits/nuts, 57 % for wheat, and 79 % for oilseeds occurring in regions with high water stress. Irrigation of wheat (35 %), paddy rice (31 %), and cotton (16 %) dominate the water FP connected to water stress in South East and Central Asia. In China, irrigation of cotton (39 %), wheat (26 %), and paddy rice (15 %) contributes most.

Main sources of uncertainties of the projections of water FP are from land use projections and variations of assumed water intensity of yield changes. Thus, the range of potential variation of the water FP in 2030 is higher than for land (Tab. 1).

Climate footprint

Compared to world average the German BE contributions to total domestic GHG emissions covered by the UN Framework Convention on Climate Change are rather low (11-12 % in Germany vs. 17-18 % in the world). However, when looking at the climate FP, the picture changes. In -2015, the BE climate FP of German consumption amounted to 1.9 t CO₂eq per person and thus substantially exceeded the global average of slightly above 1 t per person (Figure 1e). More than half of this climate FP consists of emissions on foreign territories (and therefore are not covered by Germany's NDCs under the Paris Agreement).

With continuing past trends, the BE's domestic emissions will only be reduced slightly, by 13 % from 2000 to 2030, much less than the expected reduction of the FP of total

consumption (-37 %). Nevertheless, it is expected that in 2030 Germany's total climate FP will still exceed the domestic GHG emissions of the BE by a factor of more than 1.5. The BE climate FP of German exports substantially increased in the recent past (from 750 kg per person in 2000 to about 900 kg per person today) and may be expected to grow slightly until 2030.

While for the economy as a whole and also its total climate FP CO₂ emissions contribute more than 75 %, a BE-specific analysis of domestic emissions and FPs shows a balanced contribution of three greenhouse gases: CO₂, CH₄ and N₂O indicating the relevance of ruminant farming and fertilizer management on the fields, resp.

Crop farming, livestock farming and other BE activities contribute 30 %, 46 % and 23 %, resp., to global average climate FP of the BE. For the German BE's climate FP of consumption the portions are rather similar (28 %, 44 % and 28 %, resp., in 2015). For the contribution of livestock farming a further slight decline to 43 % in 2030 may be expected, if current trends are prolonged to the future.

Within the total German economy, the contribution of BE to territorial GHG emissions was 11.9 % (-108 Mt CO₂eq) in -2015. At the same time the contribution of BE climate FP to the total climate FP of consumption was 15.2 % (160 Mt CO₂eq). Until 2030, without further policy action, the climate FP of BE is expected to decline less pronouncedly than the climate FP of the whole German economy. With implementation of the climate action programme 2030²⁴ the BE share will probably even be higher.

Value added and employment by BE

There had been high hopes linked with bio-based transformation of the economy which has been seen as the future foundation of economic growth^{1,2}. Indeed, there has been a certain growth of for the German BE from 222 billion EUR₂₀₁₅ in 2000 to 248 billion EUR in 2015,

and until 2030 one may expect further increase to 316 billion EUR₂₀₁₅. Measured in Purchaser Power Parities (PPP), the BE contribution to value added per person in Germany is nearly twice as high as on global average. However, this portion represents about 8 to 9 % of total value added generated in Germany, compared to 14 to 16 % global average, and these shares might not increase until 2030.

The contribution of the BE to employment in Germany (10 % to 12 %) is slightly higher than to value added. Globally, in 2015 still more than one third of all persons engaged could be attributed to the BE. Looking at the BE related socio-economic FPs (Fig. 1f,g) shows that Germany is as generous in spreading benefits from the BE around the world as it is regarding environmental burden. On average every consumer in Germany contributes to BE value added somewhere around the world in the order of 2000 to 2500 PPP int. \$₂₀₁₁. At the same time about 0.2 BE persons engaged in other countries can be attributed to the average consumer in Germany, while within the country it is less than 0.04 BE persons.

Crop farming and livestock farming contribute the lowest share to value added and remain on a rather low level. Even negative dynamics in price-deflated value added can also be observed in some other old-established parts of BE (e.g. forestry and fishery and manufacturing of food & beverages or textiles) and are contrasted by innovative or dynamic BE parts (e.g. manufacturing of bio-based chemicals or restaurant services) that showed above average growth rates in the last decades.

It must be taken into account that contributions of new branches such as biotechnology and their products until now cannot be measured sufficiently well. One may expect, nevertheless, that in future combinations of biomass- and mineral-based processes will be used, and the degree to which natural resources can be used efficiently will determine both environmental and economic competitiveness leading to further growth.

This article provides a synopsis of key indicators of the German BE with a focus on global environmental FPs. It shows that the territorial perspective needs to be complemented by a transnational perspective. In terms of sustainability, a first orientation on whether a country exerts disproportionate pressure is possible by comparing FP levels with global or continental average.

On a per person basis, agricultural biomass consumption of Germany exceeds global average; consumption of primary timber is at a level which can be supplied sustainably at European scale; agricultural land use has exceeded global average in the past, and cropland use may still be beyond average and sustainable levels in 2030 without additional measures. In particular, climate FP of German BE is disproportionally high, also in relation to the rather moderate contribution to socio-economic performance.

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Methods

Input-Output-based footprint analysis

BE related FPs of supply and consumption (incl. capital formation) as well as those for exports were determined for GHG emissions and resource use (biotic materials, land, water). Total supply FPs comprise emissions/resource use on domestic territory plus those associated with imports. Consumption FP deducts FP of exports from total supply FP^{25,26,27}.

In order to trace back imports to the countries of origin (of the raw materials), the global multi-regional input-output data base EXIOBASE was used. Its most recent data set for the assessment of BE related FPs (v3.4) has been released in July 2018 and covers the historical period from 1995 to 2011 on a yearly base^{28,29}. By assessing the database for monitoring the BE in Germany some major shortcomings (e.g. regarding the CO₂ emissions by agriculture in Germany) have been detected and fixed.

In a first step this corrected historical dataset has been prolonged up to 2017 by means of a now-casting procedure, that translates knowledge on developments in the recent past (2011-2017) from official statistics into an updating of the whole database. The statistics that have been used in this procedure range from the World Development Indicator database by Worldbank (e.g. for observations on the development of the different GDP components in all countries and rest of world-regions) to the FAO database (e.g. for observations on the production of crops in monetary terms as well as in physical units).

Projections of future development have assumed continuation of recent trends and have been oriented towards SSP2^{30,31}. Socio-economic trends stem from UN³² regarding population. For GDP, OECD quantifications have been used³³. For Germany, we use detailed projection data until 2030 from a long-term trend scenario that has been developed with close feedback from different German public institutions as a basis for the national vulnerability analysis³⁴. For updating the data framework of EXIOBASE until 2030 (including not only the MRIO data for the economic supply and use interdependencies, but also satellite data for environmental and socio-economic extensions) we could refer to two inhouse models (PANTA RHEI, GINFORS) that already translated this business-as-usual paradigm and exogenous guidelines into quantitative EE-IO model results from a national perspective as well as from a global, multinational perspective^{35,36,37,38}.

The method for the assessment of BE related FPs by means of an application of global environmentally extended MRIO EXIOBASE can be summarized as follows: the multi-regional vector of consumption incl. capital formation (= final inlands use of country c differentiated for products and their countries of origin), is denoted as $mrfiu_c$ and the matrix of multi-regional input-output coefficients as $MRIOA$. This standard repertoire of MRIO analysis in our case is expanded by a number of matrices and vectors. For the following examples these expansions cover:

- $mrexp_c$ ~ multi-regional vector of exports by country c ,
- $MREXI_AGBI$ ~ a square-matrix with entries on the main diagonal for the extraction intensity of production (in kg per EUR of production) for agricultural biomass,
- $mrbes$ ~ a square-matrix with entries on the main diagonal for the bioeconomy share of the respective industry/product
- $mremi$ ~ a square-matrix with entries on the main diagonal for the emission intensity of production (in kg CO₂ equivalents per EUR of production) for all GHG together.

- $mrvai$ ~ a square-matrix with entries on the main diagonal for the value added intensity of production (in EUR value added per EUR production).

Then the (sum of the multi-regional vector of the) biomass agriculture FP of consumption and capital formation in country c ($mrcfp[agbi]_c$) can be calculated as follows:

$$(1) CFP_{agbi} = \sum mrcfp[agbi]_c = MREXI_AGBI * MRBES * (I - MRIOA)^{-1} * mrfiu_c$$

The (sum of the multi-regional vector of the) BE related ghg FP of consumption and capital formation in country c ($mrcfp[begh]_c$) is given by:

$$(2) CFP_{begh} = \sum mrcfp[begh]_c = MREMI * MRBES * (I - MRIOA)^{-1} * mrfiu_c$$

The (sum of the multi-regional vector of the) BE related value added FP of consumption and capital formation in country c ($mrcfp[beva]_c$) is given by:

$$(3) CFP_{beva} = \sum mrcfp[beva]_c = MRVAI * MRBES * (I - MRIOA)^{-1} * mrfiu_c$$

The respective (sums of the multi-regional vectors) for the FP of exports ($efp[agbi]$, $efp[begh]$) and $efp[beva]$ are calculated by assessing the multiregional vector of exports instead:

$$(4) EFP_{agbi} = \sum mrefp[agbi]_c = MREXI_AGBI * MRBES * (I - MRIOA)^{-1} * mrexpc$$

$$(5) EFP_{begh} = \sum mrefp[begh]_c = MREMI * MRBES * (I - MRIOA)^{-1} * mrexpc$$

$$(6) EFP_{beva} = \sum mrefp[beva]_c = MRVAI * MRBES * (I - MRIOA)^{-1} * mrexpc$$

Forestry biomass footprint

The material matrix F of Exiobase 3.4 comprises seven forest-biomass related use classes. Three of them exclusively contain forest biomass other than wood and are therefore not of interest for the intended FP calculation in this paper. The remaining four are "coniferous wood – industrial roundwood, coniferous wood – woodfuel, non-coniferous wood – industrial roundwood and non-coniferous wood – woodfuel". In the original version of Exiobase 3.4, the amount of wood in the respective use class and country is taken from the FAO, but converted from m³ to kilotons. In the adapted version of Exiobase used for this analysis, the original FAO values are used for the calculation with the unit m³.

Land-use modelling

The LandSHIFT model^{39,40} was applied to calculate the spatial allocation of agricultural land on a global raster with a spatial resolution of 5arc minutes (= 9x9 km at the Equator). This included rain-fed and irrigated cropland as well as grazing land. Depending on the simulation year, LandSHIFT operated in two different operation modes, i.e., the "initialisation" and "scenario" mode.

For the years 1995, 2000, 2005, 2010 and 2015 a sequence of historical land-use maps were generated in initialisation mode by fusing remote sensing data on land cover^{41,42} with statistical data from FAOSTAT on the area of crop cultivation and grazing⁸.

For the year 2020, 2025, and 2030 land-use maps were generated in scenario mode by allocating as much crop cultivation and grazing area as needed to reach prescribed quantities of production specific to all crops and livestock. The relation between area and production was established using gridded data on potential yields (cropland) and net primary production of grasslands (livestock grazing) as provided by the LPJmL model⁴³. The scenario-mode simulations were based on the patterns of agricultural area resulting from the initialisation in 2015 and driven by trend projections of crop and livestock production. At the start of the scenario simulation, calibration factors to convert potential crop yields into actual crop yields (by crop and country)

were calculated and applied for subsequent time steps. For livestock grazing, the initial calibration was done by calculating the fixed fraction of livestock that can be fed by the grass production on the grazing area.

Crop cultivation differentiates twelve primary crop classes, each under irrigated and rain-fed management. The crop classes generally follow the definition underlying EXIOBASE with the classes paddy rice, wheat, cereal grains nec (not elsewhere classified), plant-based fibres, oil seeds, vegetables/fruits/nuts, sugar cane/sugar beet, and crops nec. Because of their importance for the land and/or water FP, soy beans and oil palm (part of oil crops) as well as cotton (part of plant-based fibres) were modelled separately. In addition, fodder crops were modelled, though under rain-fed management only.

Data on area and production of crops and livestock was taken from FAOSTAT⁸. Harvested area for each crop was converted into physical area under irrigated and rain-fed management using results from SPAM⁴⁴ for 2005⁴⁵ (time steps 1995, 2000, 2005) and 2010⁴⁶ (2010 and later). The physical area of fodder crops was informed by the area under temporary meadows and pastures from FAOSTAT. Due to a lack of data on production of fodder crops in FAOSTAT, the estimates of grass production in EXIOBASE for 44 countries and 5 “rest-of-the-world” regions were used and, if necessary, downscaled to country level using potential grass production on temporary meadows and pastures as a scaling factor.

Land Footprint

The German agricultural land footprint (land-FP) comprises the cropland and grassland areas used for the production of fully or partly biomass-based products consumed in Germany, both domestically and abroad. For imports to Germany, the regions of origin, the crop groups and their assignment to crop groups are determined on the basis of international trade links covered in EXIOBASE (compare material FP). The global area occupation is also determined and the global and German area occupation per person³² is calculated.

Information on the characteristics of the area occupied is integrated into the agricultural FP, which allows a risk assessment of impacts on biodiversity. Thus, it is assumed that the conversion of (1) primary forest⁴⁷, (2) biodiverse forest, (3) biodiverse grassland, (4) other biodiverse land fusing information on biodiversity^{48,49} with land cover⁴², (5) peatland⁵⁰, (6) wetlands⁵¹, (7) forest⁴², (8) unused grassland (grassland types in CCI⁴² not used for grazing by LandSHIFT) and (9) used grassland to arable land is associated with an increased risk for biodiversity (risk areas). In case of overlaps, an area is assigned to the category that is listed first in that order. For areas "in use" such as used arable land (including fallow land) and settlement areas, this risk is estimated to be significantly lower. In the case of grassland, already used grassland is generally assumed to be "in use". A land conversion in protected areas⁵² is excluded from conversion.

The land conversion rate is calculated as the rate at which risk areas are converted from the beginning to the end of a time step of five years. The allocation of risk areas in the country of origin takes into account changes in imports to Germany and changes in production in the country of origin (e.g. increased yields). If, for example, imports to Germany do not increase or increase only to the extent of the increase in production in the country of origin, imports to Germany are allocated primarily to land in the "in use" category and subordinate to converted land. Increases in imports that go beyond this are directly allocated to the conversion of risk areas.

Water footprint

The water FP is defined as the irrigation water withdrawals associated with material flows of primary crops to the German BE. Total material flows (=production) were split into flows for domestic consumption (default for the water FP) and exports. Estimates of the water FP were aggregated according to water stress levels in the watersheds where the respective crops are cultivated, based on the land-use modelling results. Material flows, the regions of origin and

their assignment to primary crops were determined on the basis of international trade links covered in EXIOBASE.

The calculation of the water FP was done in three steps:

(1) Information on crop-specific irrigation water withdrawals was calculated based on the global land-use maps provided by LandSHIFT. For each cell with an irrigated crop type, irrigation water requirements were determined with the CROPWAT model⁴⁷ based on bias-corrected climate data from the IPSL-CM5A-LR general circulation model for RCP6.0⁵⁴ as described in Schaldach et al.⁴⁰. In addition, the location of the respective irrigated area was combined with spatial information on regional water stress. Regional water stress in about 140 000 (sub-)basins globally was expressed as the ratio of water withdrawals to availability (wta)⁵⁵ using output on freshwater availability of the WaterGAP model^{56,57,58,59} and estimates of water withdrawals for households, industry⁶⁰ and agriculture representative for year 2005. These values were further grouped into three classes of high ($wta > 0.4$), medium ($0.2 < wta \leq 0.4$), and low ($wta \leq 0.2$) water stress⁶¹.

(2) For every country/region and irrigated crop type, the average IWW needed to produce 1 t of that crop was calculated taking into consideration the aforementioned water stress classes. Then, these water intensities were multiplied by the crop specific material flows.

(3) These contributions to the water FP in a given year, specific to a unique combination of source region, water stress level at the source, and primary crop, were summed to the total water FP and its relevant fractions (e.g., water FP associated with a given crop or water FP in regions with high water stress), respectively.

The largest source of uncertainty of the modelled irrigation water withdrawals and, hence, the water FP was that the relationship between crop water requirements (CWR) and crop yield was not covered in detail by our modelling approach. Although CWR was modelled as a

function of climate conditions, the effect of other changes affecting average actual crop yields, e.g. management, fertilizer application, or improved crop varieties, on CWR were neglected. The resulting range of uncertainty was assessed by calculating a maximum and minimum estimate of the water FP. The maximum estimate assumed CWR per unit area changing by the same factor as actual irrigated crop yields at constant efficiency of irrigation systems. The minimum estimate assumed CWR depending on climate conditions only and irrigation efficiency changing by the same factor as irrigated crop yields, while irrigation efficiency was limited to a maximum of 0.9 (10 % losses).

Climate footprint

The climate FP allocates emissions of greenhouse gases, that are measured on a territorial basis to the final users of the products. It is assumed that each unit of GHG emissions has the same effect regardless of where it is emitted, as it contributes equally to global warming. For the ex-post assessment of BE related climate FPs the EXIOBASE database already offers all necessary information:

1. The global economic interconnectedness that is reported in the (monetary) MRIO tables
2. The dependence of the different industries from biotic inputs (for the determination of BE shares)
3. The industry-specific emission intensity of production for 6 different greenhouse gases (CO₂, N₂O, CH₄, HFC, PFC, SF₆) in CO₂ equivalents

For the projection overall trends with regard to economic³³ and emission development³⁰ are in line with SSP2 developments on global level and a national reference scenario³⁴. Structural developments not available from the above sources mainly prolong historical trends as quantified in the models PANTA RHEI and GINFORS until 2030. They have translated into EXIOBASE compatible observations and classifications (see also above).

492

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594

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597 **Author Contributions**

598 Stefan Bringezu designed the approach, coordinated the research and contributed to
599 methodological development of FP calculations. Martin Distelkamp and Christian Lutz
600 conducted MRIO analysis, calculated biomass material FP, analyzed climate FP and socio-
601 economic performance. Florian Wimmer and Rüdiger Schaldach conducted land use
602 modelling and water FP calculations. Klaus Hennenberg and Hannes Böttcher attributed land
603 FP and land transformation to land use categories. Vincent Egenolf calculated the forest
604 material FP.

605 **Competing Interests**

606 Authors declare no conflict of interest.

607

Fig. 1 Trends of key environmental and socio-economic footprints (FP) of the German bioeconomy: (a) Agriculture biomass FP, (b) Forest biomass FP, (c) Agriculture land FP, (d) Water FP, (e) Climate FP, (f) value added FP and (g) employment FP. PPP = Purchase Power Parity.

Fig. 2. Agriculture land footprint of the German bioeconomy: (a) Trends of grassland and cropland for global and domestic consumption, (b) land use change induced by German consumption of agricultural biomass, (c) global land use change induced by agriculture.

Figure 3

Fig. 3. Water footprint of annual consumption of agricultural goods in Germany by primary crop class, categorized by water stress level.

Figure 4

Fig. 4. Bioeconomy-based GHG emissions: (a) global average, (b) climate footprint of consumption of Germany, and (c) emissions from German territory. Other BE: forestry, fisheries, manufacturing of biotic resources (e.g. food & beverages, bio-based chemicals), wood-based construction, bioenergy, restaurants

Figure 5

Fig. 5. Bioeconomy-based value added and employment: (a) global average, (b) footprint of consumption of Germany, and (c) socioeconomic impact within Germany. Other BE: forestry, fisheries, manufacturing of biotic resources (e.g. food & beverages, bio-based chemicals), wood-based construction, bioenergy, restaurants

Figures

Figure 1

Trends of key environmental and socio-economic footprints (FP) of the German bioeconomy: (a) Agriculture biomass FP, (b) Forest biomass FP, (c) Agriculture land FP, (d) Water FP, (e) Climate FP, (f) value added FP and (g) employment FP. PPP = Purchase Power Parity.

Figure 2

Agriculture land footprint of the German bioeconomy: (a) Trends of grassland and cropland for global and domestic consumption, (b) land use change induced by German consumption of agricultural biomass, (c) global land use change induced by agriculture.

Figure 3

Water footprint of annual consumption of agricultural goods in Germany by primary crop class, categorized by water stress level.

Figure 4

Bioeconomy-based GHG emissions: (a) global average, (b) climate footprint of consumption of Germany, and (c) emissions from German territory. Other BE: forestry, fisheries, manufacturing of biotic resources (e.g. food & beverages, bio-based chemicals), wood-based construction, bioenergy, restaurants

Figure 5

Bioeconomy-based value added and employment: (a) global average, (b) footprint of consumption of Germany, and (c) socioeconomic impact within Germany. Other BE: forestry, fisheries, manufacturing of biotic resources (e.g. food & beverages, bio-based chemicals), wood-based construction, bioenergy, restaurants