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Environmental and socioeconomic footprints of the German bioeconomy

Stefan Bringezu[1]✉, Martin Distelkamp[2], Christian Lutz[2], Florian Wimmer[1], Rüdiger Schaldach[1], Klaus Josef Hennenberg[3], Hannes Böttcher[3] and Vincent Egenolf[1]

Hoping to support sustainability, countries have established policies to foster the bioeconomy (BE), based on the use of biomass and knowledge on biological principles. However, appropriate monitoring is still lacking. We estimate global key environmental footprints (FPs) of the German BE in a historic analysis from 2000–2015 and in projection until 2030. Overall, the agricultural biomass FP is dominated by animal-based food consumption, which is slightly decreasing. The forestry biomass FP of consumption could potentially shift from net import to total supply from domestic territory. Agricultural land use for consumption is triple that of domestic agricultural land (which covers half of Germany) and induced substantial land use change in other regions from 2000–2015. The FP of irrigation water withdrawals has decreased over 2000–2015 and might continue to decline in absolute terms by 2030, but the share of supply regions with water stress might increase. The climate FP of BE contributes 18–20% to the total climate FP of domestic consumption, while employment makes up 10% and value added only 8% of the total German economy. These findings imply that sufficient monitoring of the BE needs to consider both production and consumption perspectives, as well as global FPs of national economies.

Countries have established policies to foster the development of a bioeconomy (BE), expecting to promote sustainability. In particular, opportunities are seen in the shift towards a renewable resource basis, additional income for farmers and increased innovation by biotechnology, potentially leading to higher income and stabilization of employment. Challenges seem to be mainly rooted in the limited availability of land to provide biomass for various purposes. However, monitoring of the BE's performance is widely lacking. In this Article, we comprehensively analyse environmental and key socioeconomic indicators of the German BE, revealing changes of environmental burden and socioeconomic benefits to other regions over time. We conclude that adequate monitoring of the BE will have to consider both domestic and foreign impacts.

Many still believe in a basic misconception: biomass is renewable and its use would generally be sustainable. Several countries, such as the United States, Sweden and Germany, as well as the European Union and the Organisation for Economic Co-operation and Development, have established policies to foster a shift towards a BE[1,2]. The intention was mainly to replace fossil- and mineral-based resources with biomass, and there have been high hopes with regards to additional income for farmers and foresters through bioenergy and biomaterials, sustaining rural development, and economic growth through innovations in biotechnology[3]. However, as a consequence of the increased use of biomass, unwanted side effects have emerged. These include land use change, directly or indirectly induced by a growing demand for food, fibres and fuels, leading to an overexploitation of biotic resources, water and land domestically and internationally[4,5], as well as losses of biodiversity[6] and increased greenhouse gas (GHG) emissions in same cases[7]. Meanwhile, it has become clear that any BE would only be sustainable when following important principles[8] 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 the biofuel industry) have been created, comprehensive monitoring of the actual performance of the 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 BE 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 with which to assess the environmental effects of human consumption[17], and have already been applied for the German economy as a whole[18].

In this Article, we provide a comprehensive analysis of past and projected resource and climate footprints (FPs) of the German BE and compare them with established indicators of socioeconomic performance, such as employment and value added. Building on conceptual[15,19] and empirical[17,20] work, we concentrate on materials (forest and agricultural biomass), agricultural land, irrigation water withdrawals and climate FPs as essential parts of a future monitoring system. We employed data and models reflecting the material flows from biomass production on fields and in forests to manufacturing and final consumption or export of products. Imports of the German BE were traced back to the countries of origin, accounting for domestic and international interrelations of economic sectors via trade. FPs were calculated for the historic period from 2000–2015, for a trend projection until the year 2030, and were compared with global per-person averages.

Results

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 withdrawals (water FP) and GHG emissions (climate FP). The FPs of production of the German BE account for the

[1]Center for Environmental Systems Research, University of Kassel, Kassel, Germany. [2]Institute of Economic Structures Research (GWS), Osnabrück, Germany. [3]Öko-Institut, Darmstadt, Germany. ✉e-mail: bringezu@uni-kassel.de

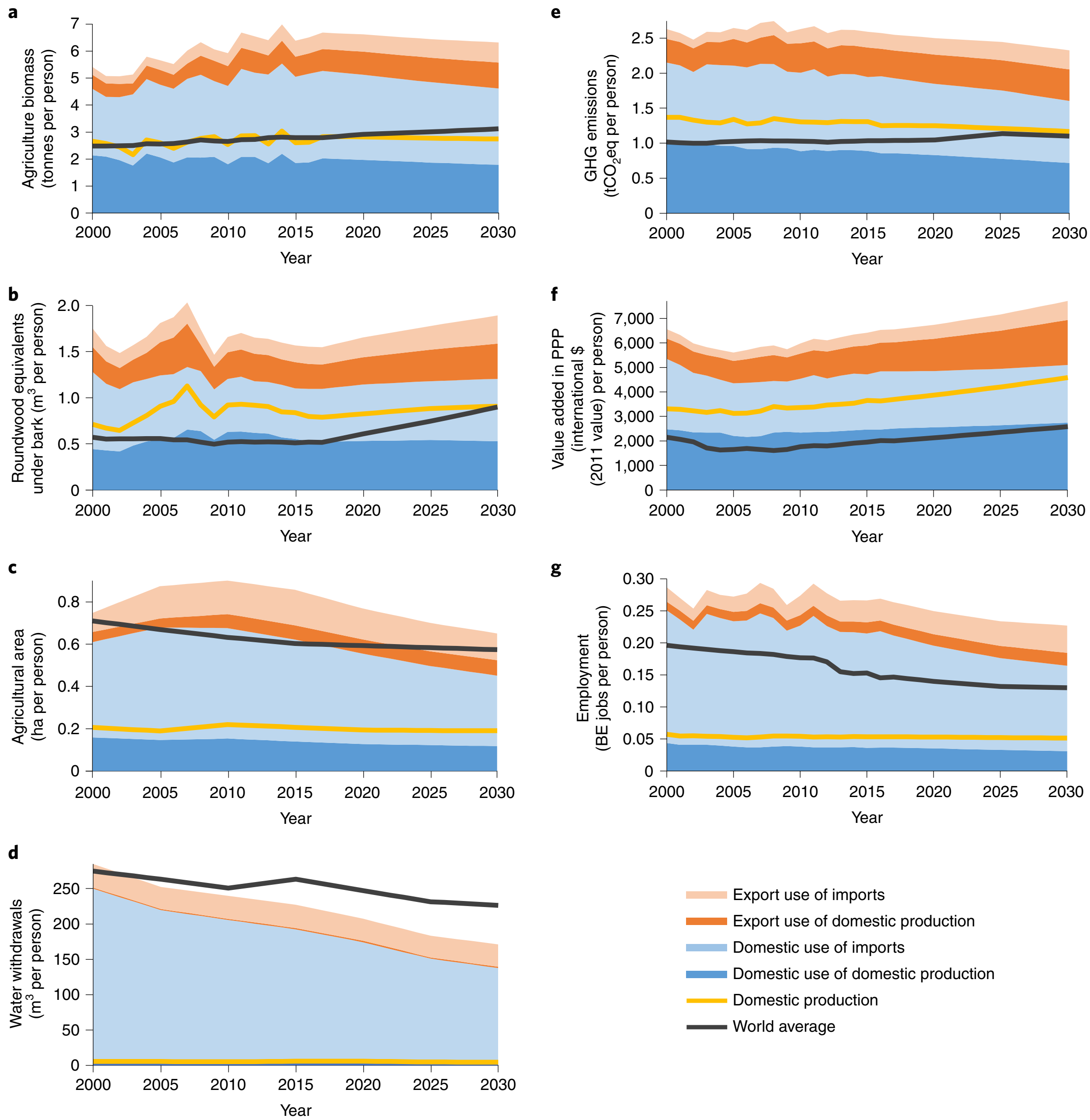

Fig. 1 | Trends of the key environmental and socioeconomic consumption FPs of the German BE. a, Agriculture biomass FP. **b**, Forestry biomass FP. **c**, Agriculture land FP. **d**, Water FP. **e**, Climate FP. **f**, Value added FP. **g**, Employment FP. PPP, purchasing power parity.

global pressures of total supply, starting with domestic primary production and upstream processes of imports (beginning with agriculture and forestry in the countries of origin). When measuring the FPs of domestic consumption (of goods), the FPs of exports are deducted from the production FPs, considering their origin from inland or foreign sources. The environmental FPs are complemented by socioeconomic indicators of value added and employment.

Agricultural biomass FP. In 2015, Germany harvested 214 Mt of agricultural biomass on its own territory. The trade balance for directly traded agricultural products revealed an import dependency (31 Mt of imports versus 19 Mt of exports). Considering the FPs of imports and exports, this dependency becomes more pronounced, with direct and indirect flows of biomass accounting for 311 Mt of imports versus 110 Mt of exports, resulting in an agricultural biomass FP of consumption of 415 Mt. One reason for these higher differences when considering the upstream flows is that foreign fodder crops and crop residues are accounted for with the trade of animal-based products.

In 2015, the agricultural biomass FP of consumption amounted to 5.0 t per person and exceeded the global average of 2.8 t per person of agricultural biomass consumption by 81% (Fig. 1a). When ongoing trends of shifts in dietary patterns, such as slightly decreasing meat consumption in Germany, are projected to continue to 2030, this exceedance may decrease to below 50%. For other countries and regions, we assumed the trends according to the middle-of-the-road scenario that is widely used for climate modelling.

Globally, about 14% of harvested agricultural biomass is used in the form of cereal grains. Another 14% are oil seeds or sugar crops and about 15% are other primary crops such as vegetables or fruits. The remaining 57% are used for fodder crops, grazed biomass and used crop residues such as straw. These shares are similar for the composition of Germany's agricultural biomass FP[21]. Considering that even cereal grains, oil seed, sugar crops and other primary

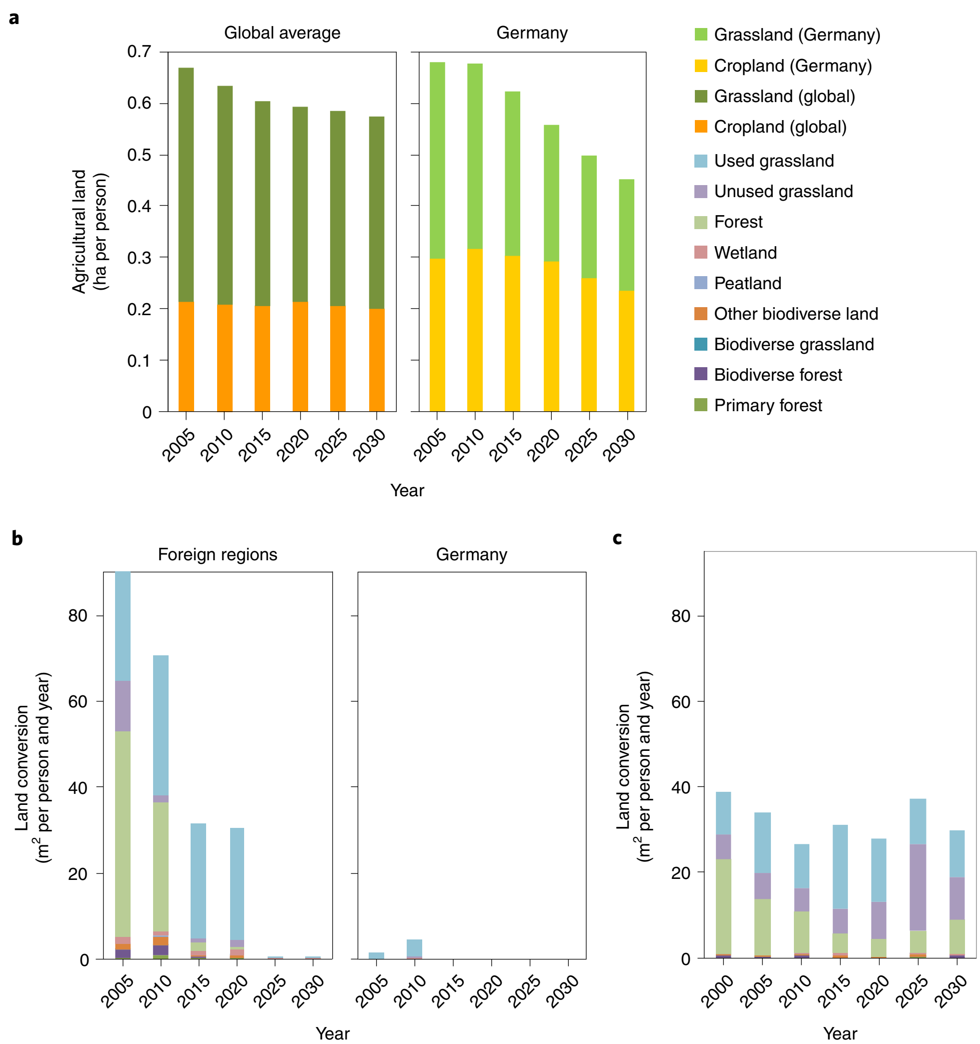

Fig. 2 | Agriculture land FP of the German BE. a, Trends of grassland and cropland for global and domestic consumption. **b**, Land use change induced by German consumption of agricultural biomass. **c**, Global land use change induced by agriculture.

crops are partly used for energy, processing or feed purposes, we can conclude that only a minor part of Germany's agricultural biomass FP is directly used for food purposes.

Forestry biomass FP. Germany is a net importer of roundwood equivalents under bark (Fig. 1b). The forestry FP of domestic consumption exceeded domestic roundwood production by about 45% on average from 2000–2015. The past level of the consumption FP of 95.1 Mm^3 roundwood equivalents on average could have been completely supplied from Germany's domestic territory as it lay within the potential sustainable national roundwood production range of 86–114 Mm^3 roundwood equivalents in 2015 and 79–118 Mm^3 roundwood equivalents in 2030[22]. For exports, ongoing trends would lead to rising volumes of up to 32 Mm^3 roundwood equivalents by 2030. In that case, the total demand for roundwood equivalents for domestic production would reach a level that could no longer be supplied from Germany's own territory alone.

The average German consumption of roundwood equivalents has been $1.17 \pm 0.06\,m^3$ per person. Thus, it is within and does not exceed the range of 1.1–1.4 m^3 per person, which has been considered a safe and just maximum roundwood consumption boundary regarding the productivity of European forests[23]. Globally, the consumption of roundwood equivalents is on average notably lower than Germany's (Fig. 1b) as many regions are void of forests and use other materials instead. Thus, with regard to availability and culture, a comparison seems more adequate with European forest productivity.

Agricultural land FP. Germany uses an area three times as large as its domestic agricultural area to supply its consumption. In 2015, the land FP was 51 Mha, compared with 17 Mha of domestic agricultural area. The land FP might decrease in the coming years (for example, due to reductions in meat consumption and food waste[24,25], as well as further increases in crop productivity[26]; Fig. 1c). The German land FP of consumption would fall below the global per-person average in 2030. However, cropland use, which is the most intensive form of agricultural land use, might still be above average in 2030 (Fig. 2a), and it would also exceed the 0.20 ha per person that has been suggested as a proxy safe operating space[27].

The increased consumption of biomass in Germany in the early 2000s has not only led to levels of land use per person above global averages. It has also contributed to substantial land transformation, primarily in other regions of the world (Fig. 2b). Whereas the global average annual transformation rate between 2000 and 2015 fluctuated between 27 and 39 m^2 per person (Fig. 2c), the German induced foreign land use change per year started with 90 m^2 per

Table 1 | Variation of agricultural land and water FPs, projected for 2030 for domestic consumption, exports and production

	Agricultural land FP (Mha)			Water FP (km³)		
	Consumption	Exports	Production[a]	Consumption	Exports	Production[a]
Maximum[b]	43.1	18.6	51.8	15.1	3.6	18.7
Medium[c]	37.6	16.7	45.0	11.5	2.8	14.3
Minimum[d]	33.1	15.4	38.7	5.4	1.3	6.7
Range (%)	−12 to +15	−8 to +12	−14 to +15	−53 to +32	−54 to +28	−53 to +31

[a]Domestic primary production plus the FP of imports. [b]Compared with ongoing trends: −20% lower yield increases; +20% higher rate for new built-up areas; +34% higher rate for rewetting of organic soils; crop water requirements (CWR) per unit area changing by the same factor as actual irrigated crop yields; constant irrigation efficiency. [c]Projection of current trends: CWR depending on climate conditions only; constant irrigation efficiency. [d]Compared with ongoing trends: +20% higher yield increases; −20% lower rate for new built-up areas; −34% lower rate for restoration of wetlands; CWR depending on climate conditions only; irrigation efficiency changing by the same factor as actual irrigated crop yields.

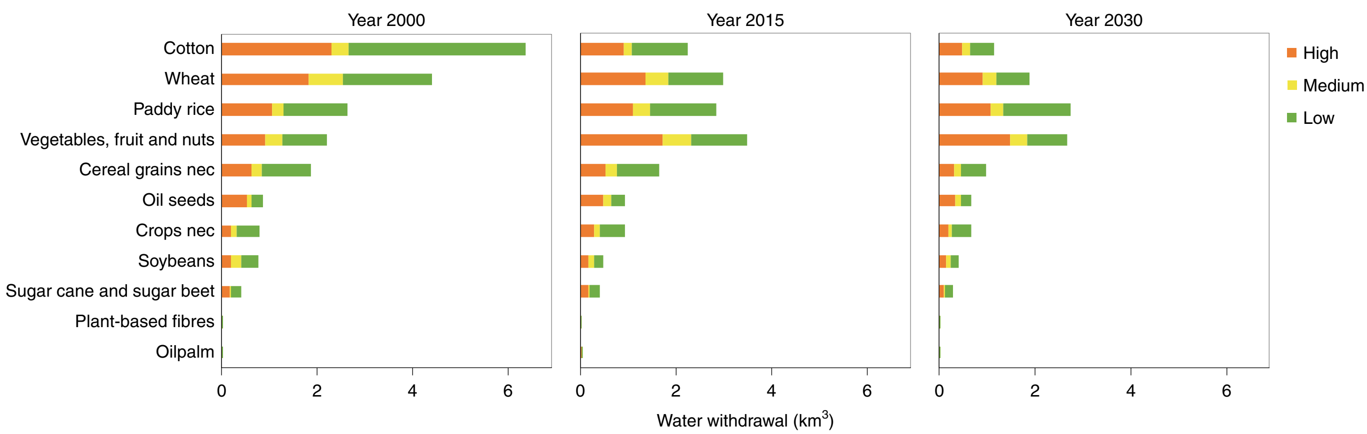

Fig. 3 | Water FP of annual consumption of agricultural goods in Germany by primary crop class, categorized by water stress level. Results are presented for the years 2000, 2015 and 2030. nec, not elsewhere classified.

person in the period 2000–2005, decreased to 32 m² per person in 2015 and might go down to zero until 2030. This indicates that Germany exerted major pressures on global land use change and loss of natural habitats due to its increases in biomass demand, which were higher than yield increases, in past decades. From 2000–2005, mainly forest was converted to agricultural land, while from 2010 onward, mainly used grassland was transformed for more intensive uses. It is likely that the conversion of natural and semi-natural land, as well as the intensification of agricultural and forestry practices, led to losses of ecosystem services and biodiversity[28].

Projection data on future development are uncertain, not only because of the not yet considered COVID-19 impact, but also due to variation in yield increases, assumptions on the development of built-up land and the restoration of wetlands on former peatland, and varying substitutions of imports by domestic production. As a consequence, in 2030, the medium land FP of consumption would be 37.6 Mha and the range would be −12 to +15%. The land FP of German BE production could range from −14 to +15% around a medium value of 45 Mha (Table 1).

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

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

Per-person global irrigation water withdrawals afflicted with water stress are predicted to decrease from 125–101 m³ (−19%) between 2000 and 2030. The part of the German water FP stemming from water-stressed regions might decrease from 96–60 m³ per person (−37%) in the same period. Hence, the pressure on water resources per person induced by Germany's consumption of products and related irrigation water is less than the global average and is projected to decrease.

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 total irrigation water withdrawals from regions with high water stress are attributable to Germany's consumption.

In the Middle East, irrigation of vegetables, fruits and nuts (52%), wheat (17%) and oil seeds (10%) contributes most to the water FP afflicted with water stress. Large parts of the Middle East

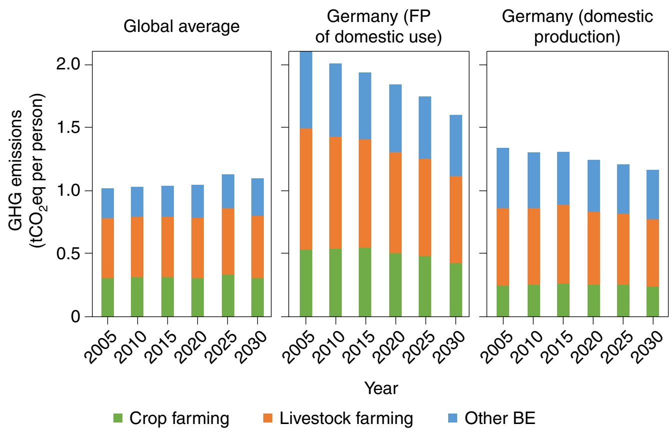

Fig. 4 | BE-based GHG emissions. Graphs are shown for the global average, climate FP of consumption of Germany and emissions from German territory. Other BE includes forestry, fisheries, manufacturing of biotic resources (for example, food and beverages and bio-based chemicals), wood-based construction, bioenergy and restaurants.

suffer from high water stress, with 61% of water withdrawals for vegetables, fruits and nuts, 57% for wheat and 79% for oil seeds occurring under high water stress. Irrigation of wheat (35%), paddy rice (31%) and cotton (16%) dominates the water FP connected to water stress in South-East and Central Asia. In China, cotton (39%), wheat (26%) and paddy rice (15%) contribute most to the water FP in water stress areas.

The main sources of uncertainties in the projections of the 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 (Table 1).

Climate FP. Our calculations showed that the German BE contributions to total territorial GHG emissions covered by the United Nations Framework Convention on Climate Change (CO_2, N_2O, CH_4, hydrofluorocarbons, perfluorocarbons and SF_6) are rather low (11–12% in Germany compared with a world average of 17–18%). However, when looking at the climate FP, the picture changes. In 2015, the BE climate FP of German consumption amounted to 1.9 tCO_2eq per person and thus substantially exceeded the global average of slightly above 1 t per person (Fig. 1e). More than half of this climate FP consists of emissions on foreign territories (which are not covered by Germany's nationally determined contributions under the Paris Agreement).

With continuing past trends, the BE's domestic emissions will only be reduced slightly, by 13% from 2000–2030, which is much less than the expected reduction of the climate FP of total consumption of all (including non-BE) goods (−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. Especially due to an ongoing globalization that led to sharp increases in Germany's meat exports, the BE climate FP of German exports substantially increased historically (from 750 $kgCO_2$eq per person in 2000 to about 900 $kgCO_2$eq 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, CO_2 emissions contribute more than 75%, a BE-specific analysis of domestic emissions and FPs shows a balanced contribution of three GHGs (CO_2, CH_4 and N_2O), indicating the relevance of ruminant farming and fertilizer management on the fields, respectively.

Crop farming, livestock farming and other BE production activities contribute 30, 46 and 23%, respectively, to the global average climate FP of the BE (Fig. 4). For the German BE's climate FP of consumption, the portions are rather similar (28, 44 and 28%, respectively, in 2015). For the contribution of livestock farming, a further slight decrease to 43% in 2030 may be expected if current trends are prolonged into the future.

Within the total German economy, the contribution of the BE to territorial GHG emissions was 11.9% (108 $MtCO_2$eq) in 2015. At the same time, the contribution of the BE climate FP to the total climate FP of consumption was 19.3% (19.8% in 2000). Until 2030, without further policy action, the climate FP of the BE is expected to decline a bit more pronouncedly than the climate FP of the whole German economy to reach 18.6% in 2030. With implementation of the new Climate Action Programme 2030[29], the BE share will probably become even higher, as the sector targets of the German government for agriculture (−36% in 2030 against 1990) are less ambitious than for other sectors, with an overall reduction target of 55% by 2030 against 1990[30].

Value added and employment by the BE. There have been high hopes for the bio-based transformation of the economy, which has been seen as the future foundation of economic growth[1,2]. Economic growth is often measured in terms of gross domestic product (GDP). Gross value added is a measure of the contribution made by a sector to GDP. Indeed, there has been a certain growth of value added in the German BE from €222 billion in 2000 to €248 billion in 2015, and until 2030 one may expect a further increase to €316 billion (all values in constant 2015 prices). Measured in purchasing power parities, the BE value added per person in Germany is nearly twice as high as the global average. However—and not surprisingly, reflecting Germany's status as a high-income country—the contribution of the BE to total value added (8–9%) is considerably lower than the global average (14–16%), and these shares might not increase until 2030.

The contribution of the BE to total employment in Germany (10–12%) is slightly higher than its contribution to value added. Globally in 2015, still more than one-third of all persons employed could be attributed to the BE. Looking at the BE-related socioeconomic FPs (Fig. 1f,g) shows that on average every consumer in Germany contributes to BE value added somewhere around the world in the order of $2,000–2,500 purchasing power parities every year (international dollars at the 2011 value). At the same time, about 0.2 BE persons employed 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 (Fig. 5). Negative dynamics in price-deflated value added can also be observed in some other traditional parts of the BE (for example, forestry and fisheries and the manufacturing of food and beverages or textiles) and are contrasted by still small innovative or dynamic BE parts (for example, manufacturing of bio-based chemicals or restaurant services) that showed growth rates of value added in Germany in the past that exceed the economy-wide averages.

Discussion

It must be taken into account that contributions of new branches, such as biotechnology and their products, until now could not be sufficiently measured. One may expect, nevertheless, that in the 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. We confirmed that measuring FPs reveals

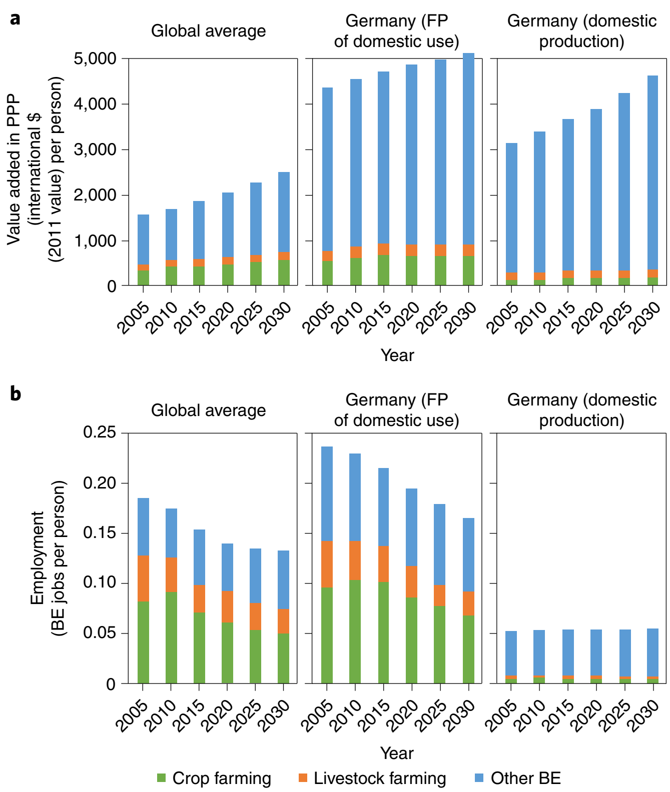

Fig. 5 | Socioeconomic performance and FPs of the German BE in the global context. a, BE-based value added. **b**, BE-based employment. In both panels, graphs are shown for the global average, FP of consumption of Germany and socioeconomic impact within Germany. Other BE includes forestry, fisheries, manufacturing of biotic resources (for example, food and beverages and bio-based chemicals), wood-based construction, bioenergy and restaurants.

important implications of domestic activities outside the national territory[15,17,19,20]. Our study has shown that the German BE has contributed substantially to land transformation in other regions, that it might continue to add to the scarcity of water in arid areas, that it uses timber from elsewhere that could be produced at home and that the GHG emissions of its consumption are much higher than is reported on the basis of the Kyoto protocol.

In terms of sustainability, a first orientation on whether a country exerts disproportionate pressure by its domestic consumption of biomass-based products is possible by comparing FP levels with global or continental averages. On a per-person basis, the agricultural biomass consumption of Germany exceeds the global average; consumption of primary timber is at a level that can be supplied sustainably at a European scale; agricultural land use has exceeded the global average in the past; and cropland use may still be beyond average and sustainable levels in 2030 without additional measures. In particular, the climate FP of the German BE is disproportionally high, also in relation to its rather moderate contribution to socioeconomic performance.

Methods

This section describes the basic calculations for all of the FPs of the German BE and provides details on the models and data used to quantify the specific environmental FPs.

Input–output-based FP analysis. BE-related FPs of production and consumption (including capital formation), as well as those for exports, were determined for GHG emissions and resource use (biotic materials, agricultural land and irrigation water withdrawals). Total production FPs comprise emissions and resource use on domestic territory plus those associated with imports. The consumption FP deducts the FP of exports from the total production FP[31–33].

To trace back imports to the countries of origin (of the raw materials), the global multi-regional input–output (MRIO) database EXIOBASE was used. Its most recent dataset for the assessment of BE-related FPs (version 3.4) was released in July 2018 and covers the historical period from 1995–2011 on a yearly basis[34,35]. The mathematical foundations of the MRIO calculations and a list of vectors and matrices for the assessment of FP indicators are given in Supplementary Table 1. The data used for the MRIO model are summarized in Supplementary Table 2. By assessing the database for monitoring the BE in Germany, some major shortcomings (for example, regarding the CO_2 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 nowcasting 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 the World Bank (for example, for observations on the development of the different GDP components in all countries and rest-of-world regions) to the Food and Agriculture Organization (FAO) database (for example, 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 the Shared Socioeconomic Pathway 2 'Middle of the road' (the baseline scenario was calculated by the Integrated Assessment Model MESSAGE-GLOBIOM from the International Institute for Applied Systems Analysis)[36,37]. This was also used for the projection of per-capita crop and per-capita livestock demand in other countries and world regions. Socioeconomic trends stem from the United Nations[38] regarding population. For GDP, Organisation for Economic Co-operation and Development quantifications were used[39]. For Germany, we used detailed projection data until 2030 from a long-term trend scenario that was developed with close feedback from different German public institutions as a basis for the national vulnerability analysis[40]. To update 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 socioeconomic extensions), we referred to two in-house models (PANTA RHEI and GINFORS) that translated the business-as-usual model and exogenous guidelines into quantitative environmentally extended input–output model results from a national perspective, as well as from a global, multinational perspective[41–44].

Our approach builds on earlier work that projected the EXIOBASE database into the future. Wiebe et al.[45]. developed a general approach for projecting a full MRIO system. The approach was expanded to a global circular economy scenario until 2030 with a focus on the energy, material and waste sectors[46]. Other recent MRIO approaches were retrospective, using today's structures and looking into, for example, more detailed policy options[47] or the role of trade for FP calculations[48].

In line with German BE policy[49] we established a definition of the BE that incorporates the following sectors on the production side:

1. Agriculture, forestry and fisheries.
2. All manufacturing sectors that use biomass as a main ingredient in their production. This means that some manufacturing sectors such as the chemical industry are only partly assigned to the BE, while others such as the food and beverages industry are fully assigned to the BE.
3. Wood-based construction.
4. Bio-based energy production.
5. Restaurant services.

To consider the German BE also on the consumption side, the FPs of both domestic consumption and exports of biomass-based products were also accounted for.

Compared with other approaches, such as by the International Resource Panel[18] including the German details, our analysis had two distinct differences: (1) our study focused on the BE part of the whole economy, which required appropriate differentiation of bio-based parts; and (2) the International Resource Panel specified some impacts on a cradle-to-material basis, meaning that use of the materials in the form of products was not included (as a result, for example, GHG emissions from the burning of fossil fuels and biomass were not considered); in contrast, our analysis included basically the full life cycle.

Forestry biomass FP. 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 were 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 was taken from the FAO, but converted from m^3 to kilotonnes. In the adapted version of EXIOBASE used for this analysis, the original FAO values were used for the calculation (with the units m^3).

Land use modelling. The LandSHIFT model[50,51] was applied to calculate the spatial allocation of agricultural land on a global raster with a spatial resolution of

5 arcmin (9 km × 9 km at the Equator), with model drivers specified on the national level. The model builds on the concept of land use systems and includes modules that represent the land use activities crop cultivation and livestock grazing. At the beginning of a simulation time step, the suitability of each raster cell for the different land use activities is determined. Thereafter, the model translates the national-level model drivers into a spatial land use pattern by allocating the specified demands for cropland and pasture on the most suitable raster cells. A more detailed overview of the model concept is provided in Supplementary Table 3, along with the datasets used for the initialization of the model.

Depending on the simulation year, LandSHIFT operated in two different operation modes (that is, initialization and scenario modes). For the years 1995, 2000, 2005, 2010 and 2015, a sequence of historical land use maps was generated in initialization mode by fusing remote sensing data on land cover[52] with national statistical data from FAOSTAT (http://www.fao.org/faostat/en/#home) on the area of crop cultivation and grazing.

For the years 2020, 2025 and 2030, land use maps were generated in scenario mode by allocating as much crop cultivation and grazing area as was needed to reach the prescribed quantities of production specific to all crops and livestock in individual countries. The relationship between area and production was established using gridded data on potential yields (cropland) and the net primary production of grasslands (livestock grazing), as provided by the LPJmL model[53]. The scenario mode simulations were based on the patterns of agricultural area resulting from the initialization 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 could be fed by the grass production on the grazing area.

The specification of crops and the database used are given in the Supplementary Information.

The lack of detail in the production data clearly influences the accuracy of the spatial allocation and, hence, the calculated FPs of fodder crops in particular. A promising way to improve our analysis in future studies will be the use of data from MRIO with country resolution that became available recently[54]. Moreover, land use modelling is limited to agricultural systems. Further improvements of our modelling approach will consider the location of managed forests and forest plantations, allowing for a spatially more detailed determination of the forest biomass FP and related effects on biodiversity.

Agricultural land FP. The German agricultural 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 (following calculation of the material FP). The global area occupation has also been determined and the global and German area occupation per person[38] has been calculated.

Information on the characteristics of the area occupied is integrated into the agricultural land FP, which allows for an assessment of the loss of natural and semi-natural habitats as an indicator for impacts on ecosystem services and biodiversity. The land cover types considered as risk areas for the accounting of the induced transformation are detailed in the Supplementary Information. It is assumed that conversion of these areas to arable land is associated with an increased risk for ecosystem services and biodiversity.

For areas in use, such as used arable land (including fallow land) and settlement areas, this risk is estimated to be definitively lower. In the case of grassland, already used grassland is generally assumed to be in use. A land conversion in protected areas[55] 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 5 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 (for example, increased yields). Imports to Germany are allocated primarily to land in the in-use category if imports to Germany have not increased in relation to the production change on in-use land for a crop in the country of origin, because in this case no additional land would have been needed for cultivation (for detailed calculations, see the Supplementary Information). Increases of imports that go beyond this are directly allocated to the conversion of risk areas in the proportions of land use types transformed by agriculture in that country as a whole.

FP of irrigation water withdrawals. The FP of irrigation water withdrawals (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 differentiated according to water stress levels in the watersheds where the respective quantities of 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.

We applied the relatively simple withdrawals-to-availability ratio[56] to assess water stress. Since its introduction, more advanced approaches with higher informative value based on water consumption have been suggested[57,58]. However, relevant improvements would require detailed modelling of water quality aspects and environmental flow requirements. As our analysis depends on a consistent water stress assessment with global coverage, such a challenge would be limited by data and would exceed the scope of our study. Given these limitations, water withdrawals are a meaningful proxy for the potential pressures on water resources in a global modelling approach. A rationale for addressing water withdrawals compared with recent concepts is given in the Supplementary Information. We report a set of irrigation water FP figures differentiated by water stress at the source.

The procedure for calculating the water FP is described in the Supplementary Information.

A major 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 (for example, 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 in addition to the standard calculations (medium). The maximum estimate assumed that the CWR per unit area changed by the same factor as actual irrigated crop yields at a 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 the irrigation efficiency was limited to a maximum of 0.9 (10% losses). For the medium estimate, CWR depending on climate conditions only and a constant irrigation efficiency were assumed.

Our estimates of global irrigation water withdrawals of about 1,700 $km^3 yr^{-1}$ (between 2000 and 2005) are lower than the findings of previous studies[59,60] ranging from 2,200–3,800 $km^3 yr^{-1}$. A possible reason for the deviation is that our approach neglects irrigation water withdrawals connected to the production of fodder crops due to missing information on the share of fodder crops produced in irrigated agriculture.

Climate FP. The climate FP allocates emissions of GHGs (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 of the 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 six different GHGs (CO_2, N_2O, CH_4, hydrofluorocarbons, perfluorocarbons and SF_6) in CO_2 equivalents

The projections of overall trends with regard to economic[33] and emission development[30] are in line with Shared Socioeconomic Pathway 2 developments on a global level and following a national reference scenario[34]. 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).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All data used in the analysis are publicly available for scientific use. In the Supplementary information, we give an overview of the data used in the analysis and specify how all data can be downloaded or obtained. Land-use maps as calculated by LandSHIFT as well as data on economic flows, biomass flows and greenhouse gas emissions are available in a data repository under the following link: https://figshare.com/ collections/Shifting_ Burden_Footprint_Trends_ of_ the_German_ Bioeconomy/5396808. Source data are provided with this paper.

Code availability

Analysis and visualization of the spatial modelling results was done using R scripts. The code is available upon request. The MRIO analysis and trend projection were conducted on the basis of an in-house modelling software package (solve). The underlying C++ code and LandSHIFT source code (C++) are available from the corresponding author upon request.

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Author contributions
S.B. designed the approach, coordinated the research and contributed to methodological development of the FP calculations. M.D. and C.L. conducted the MRIO analysis, calculated the agriculture and forestry biomass material FPs and analysed the climate FP and socioeconomic FPs. F.W. and R.S. conducted land use modelling and water FP calculations. K.J.H. and H.B. attributed land FP and land transformation to land use categories. V.E. provided data for the forestry biomass FP.

Competing interests
The authors declare no competing interests.

Additional information
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Correspondence and requests for materials should be addressed to S.B.

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Data collection	The data used in this analysis is publicly available for scientific purposes. No specific software except a web-browser was used for data collection.
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Study description	relate them to its socio-economic performance. 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. Data on biomass flows to Germany were deriverd from the Muliti-Regional-Input-Output database EXIOBASE. This historical data up to 2011 has been prolonged up to 2030 using a variety of statistical information, results from publically available forecasts and results from the econometric EE-IO model PANTA RHEI (see also supplementary information). Global land-use patterns were generated with the land-use model LandSHIFT. Information on crop water requirements and water use were calculated with the WaterGAP3 model. The footprint analysis was then conducted by linking the the global spatial data from these two models with the aforementioned biomass flows.
Research sample	The base data used for the analysis (in particular from EXIOBASE and the global spatial datasets) were publicly available. Data regarding biomass flows to Germany were extracted from EXIOBASE using the mathematical methods described in the paper.
Sampling strategy	Our methodology did not include statistical approaches that rely on a specific sampling strategy.
Data collection	We did not perform data collection but relied on previously collected published datasets. The supplementary informations includes a comprehensive overview of the datasets used for our analysis and their sources.
Timing and spatial scale	Footprints (FP) were calculated for the historic period from 2000 – 2015 and for a trend projection until the year 2030. FPs were calculated for Germany based on a global scale analysis.
Data exclusions	No data was excluded, but the analysis was done only on a subset of the EXIOBASE database (see research sample).
Reproducibility	All attempts to repeat the model simulations and data analytics were successful.
Randomization	The study is not a randomized controlled trial. We considered the data as a single sample.
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Policy information about clinical studies

All manuscripts should comply with the ICMJE guidelines for publication of clinical research and a completed CONSORT checklist must be included with all submissions.

Clinical trial registration	*Provide the trial registration number from ClinicalTrials.gov or an equivalent agency.*

Study protocol	*Note where the full trial protocol can be accessed OR if not available, explain why.*
Data collection	*Describe the settings and locales of data collection, noting the time periods of recruitment and data collection.*
Outcomes	*Describe how you pre-defined primary and secondary outcome measures and how you assessed these measures.*

Dual use research of concern

Policy information about dual use research of concern

Hazards

Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

No	Yes	
☒	☐	Public health
☒	☐	National security
☒	☐	Crops and/or livestock
☒	☐	Ecosystems
☒	☐	Any other significant area

Experiments of concern

Does the work involve any of these experiments of concern:

No	Yes	
☒	☐	Demonstrate how to render a vaccine ineffective
☒	☐	Confer resistance to therapeutically useful antibiotics or antiviral agents
☒	☐	Enhance the virulence of a pathogen or render a nonpathogen virulent
☒	☐	Increase transmissibility of a pathogen
☒	☐	Alter the host range of a pathogen
☒	☐	Enable evasion of diagnostic/detection modalities
☒	☐	Enable the weaponization of a biological agent or toxin
☒	☐	Any other potentially harmful combination of experiments and agents

ChIP-seq

Data deposition

☐ Confirm that both raw and final processed data have been deposited in a public database such as GEO.

☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links *May remain private before publication.*	*For "Initial submission" or "Revised version" documents, provide reviewer access links. For your "Final submission" document, provide a link to the deposited data.*
Files in database submission	*Provide a list of all files available in the database submission.*
Genome browser session (e.g. UCSC)	*Provide a link to an anonymized genome browser session for "Initial submission" and "Revised version" documents only, to enable peer review. Write "no longer applicable" for "Final submission" documents.*

Methodology

Replicates	*Describe the experimental replicates, specifying number, type and replicate agreement.*
Sequencing depth	*Describe the sequencing depth for each experiment, providing the total number of reads, uniquely mapped reads, length of reads and whether they were paired- or single-end.*
Antibodies	*Describe the antibodies used for the ChIP-seq experiments; as applicable, provide supplier name, catalog number, clone name, and lot number.*
Peak calling parameters	*Specify the command line program and parameters used for read mapping and peak calling, including the ChIP, control and index files used.*

Data quality | *Describe the methods used to ensure data quality in full detail, including how many peaks are at FDR 5% and above 5-fold enrichment.*

Software | *Describe the software used to collect and analyze the ChIP-seq data. For custom code that has been deposited into a community repository, provide accession details.*

Flow Cytometry

Plots

Confirm that:

- [ ] The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).
- [ ] The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).
- [ ] All plots are contour plots with outliers or pseudocolor plots.
- [ ] A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

Sample preparation | *Describe the sample preparation, detailing the biological source of the cells and any tissue processing steps used.*

Instrument | *Identify the instrument used for data collection, specifying make and model number.*

Software | *Describe the software used to collect and analyze the flow cytometry data. For custom code that has been deposited into a community repository, provide accession details.*

Cell population abundance | *Describe the abundance of the relevant cell populations within post-sort fractions, providing details on the purity of the samples and how it was determined.*

Gating strategy | *Describe the gating strategy used for all relevant experiments, specifying the preliminary FSC/SSC gates of the starting cell population, indicating where boundaries between "positive" and "negative" staining cell populations are defined.*

- [ ] Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type | *Indicate task or resting state; event-related or block design.*

Design specifications | *Specify the number of blocks, trials or experimental units per session and/or subject, and specify the length of each trial or block (if trials are blocked) and interval between trials.*

Behavioral performance measures | *State number and/or type of variables recorded (e.g. correct button press, response time) and what statistics were used to establish that the subjects were performing the task as expected (e.g. mean, range, and/or standard deviation across subjects).*

Acquisition

Imaging type(s) | *Specify: functional, structural, diffusion, perfusion.*

Field strength | *Specify in Tesla*

Sequence & imaging parameters | *Specify the pulse sequence type (gradient echo, spin echo, etc.), imaging type (EPI, spiral, etc.), field of view, matrix size, slice thickness, orientation and TE/TR/flip angle.*

Area of acquisition | *State whether a whole brain scan was used OR define the area of acquisition, describing how the region was determined.*

Diffusion MRI ☐ Used ☐ Not used

Preprocessing

Preprocessing software | *Provide detail on software version and revision number and on specific parameters (model/functions, brain extraction, segmentation, smoothing kernel size, etc.).*

Normalization | *If data were normalized/standardized, describe the approach(es): specify linear or non-linear and define image types used for transformation OR indicate that data were not normalized and explain rationale for lack of normalization.*

Normalization template | *Describe the template used for normalization/transformation, specifying subject space or group standardized space (e.g.*

Normalization template | *original Talairach, MNI305, ICBM152) OR indicate that the data were not normalized.*

Noise and artifact removal | *Describe your procedure(s) for artifact and structured noise removal, specifying motion parameters, tissue signals and physiological signals (heart rate, respiration).*

Volume censoring | *Define your software and/or method and criteria for volume censoring, and state the extent of such censoring.*

Statistical modeling & inference

Model type and settings | *Specify type (mass univariate, multivariate, RSA, predictive, etc.) and describe essential details of the model at the first and second levels (e.g. fixed, random or mixed effects; drift or auto-correlation).*

Effect(s) tested | *Define precise effect in terms of the task or stimulus conditions instead of psychological concepts and indicate whether ANOVA or factorial designs were used.*

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference (See Eklund et al. 2016) | *Specify voxel-wise or cluster-wise and report all relevant parameters for cluster-wise methods.*

Correction | *Describe the type of correction and how it is obtained for multiple comparisons (e.g. FWE, FDR, permutation or Monte Carlo).*

Models & analysis

n/a	Involved in the study
☒	☐ Functional and/or effective connectivity
☒	☐ Graph analysis
☐	☒ Multivariate modeling or predictive analysis

Multivariate modeling and predictive analysis | The MRIO analysis and trend projection has been conducted on base of an in-house modelling software package (solve). The underlying C++ code is available upon request.