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# Rising greenhouse gas emissions embodied in the global bioeconomy supply chain



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The bioeconomy is key to meeting climate targets. Here, we examine greenhouse gas emissions in the global bioeconomy supply chain (1995–2022) using advanced multi-regional input-output analysis and a global land-use change model. Considering agriculture, forestry, land use, and energy, we assess the carbon footprint of biomass production and examine its end-use by provisioning systems. The footprint increased by 3.3 Gt $CO_2$-eq, with 80% driven by international trade, mainly beef and biochemicals (biofuels, bioplastics, rubber). Biochemicals showed the largest relative increase, doubling due to tropical land-use change (feedstock cultivation) and China's energy-intensive processing. Food from retail contributes most to the total biomass carbon footprint, while food from restaurants and canteens account for >50% of carbon-footprint growth, with three times higher carbon intensity than retail. Our findings emphasize the need for sustainable sourcing strategies and that adopting renewables and halting land-use change could reduce the bioeconomy carbon footprint by almost 60%.

To stabilize global temperatures at a 1.5 °C increase and achieve net-zero greenhouse gas emissions (GHGs), promoting a sustainable and circular bioeconomy is crucial[1–3]. The bioeconomy encompasses all sectors utilizing biomass, spanning from living organisms like animals, plants, and microorganisms to derived organic materials and ecosystems. It integrates agriculture, forestry, and other land use (AFOLU), and related industries to produce food, feed, bio-based products, energy, and services[3–5]. However, the carbon footprint of the bioeconomy amounted to 17 Gt $CO_2$-eq in 2022, contributing to almost 30% of global GHGs[3]. The AFOLU sector releases $CO_2$ emissions through land use, land use change, and forestry (LULUCF)[6–8], biogenic $CH_4$ and $N_2O$ emissions from enteric fermentation, rice cultivation, and fertilizer application. Additionally, GHGs occur from energy used in biomass cultivation, harvesting, fertilizer production, transportation and processing of food, textiles, biochemicals, wood, and paper. These GHGs from the AFOLU sector and related energy supply are referred to as the carbon footprint of biomass production in this study (cradle-to-gate emissions), while downstream GHGs such as from cooking, heating, and cooling (e.g., in food stores, restaurants, canteens), as well as biomass incineration, composting, landfill decay and wastewater treatment are excluded.

Given the bioeconomy's increasing interconnectedness through international trade[9,10], understanding its global environmental implications is essential—especially for GHGs from biomass production, which often occur in different regions than where the products are consumed. However, prevailing environmental policies, such as the Paris Agreement and the EU Green Deal, only consider domestic GHGs, neglecting GHG emissions from imported commodities[11–13]. Furthermore, there is a risk that such policies inadvertently encourage the outsourcing of emissions to regions with less strict environmental policies, exacerbating the global climate crisis[14–16]. Therefore, a crucial prerequisite is access to detailed information on global supply chains and their environmental impacts. By incorporating these insights, policymakers can develop comprehensive strategies that account for the entire life cycle of products and address the intricate challenges posed by the interconnected global bioeconomy.

Environmentally-extended multi-regional input-output (MRIO) analysis[17,18] provides insights into the linkages between economic activities and their environmental implications[19]. Using MRIO analysis, GHGs from specific regions and industries can be attributed to produced goods[20,21], and final sectors supplying these goods to meet final demand can be identified[22–24]. This allows for the evaluation of GHG emissions embodied in international trade[25,26] (Supplementary Notes 1). While global MRIO databases[19,27–32] exclude emissions from LULUCF, a few studies have assessed GHGs of the AFOLU sector globally[9,33], regionally[34,35], and embodied in trade[10]. However, these studies did not account for emissions related

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to energy provision or GHGs of non-food biomass products such as textiles, biochemicals, and paper. Methodological challenges also remain, including double counting and the incomplete coverage of entire supply chains—particularly upstream activities (e.g., coal used for biomass processing) and downstream uses of specific biomass products to deliver provisioning systems. A provisioning system is an interconnected framework of ecological, technological, institutional, and social components that convert natural resources into goods and services to meet human needs[3,36–38]. Additionally, previous MRIO studies allocated GHG emissions based on total supply and demand. For example, if 80% of Brazil's beef production in a given year were consumed domestically, ~80% of the associated GHGs would be attributed to domestic consumption. However, they did not examine how changes in environmental impacts correspond to shifts in supply and demand, as can be done using a marginal allocation approach[39,40]. This marginal approach examines how specific changes over time affect the outcome relative to a baseline year. For instance, if Brazil's domestic beef consumption remained constant while beef exports increased, any rise in GHGs associated with Brazil's beef production would be attributed to exports[40].

Our study addresses these gaps by assessing GHGs associated with the extraction and processing of food, textiles, biochemicals (biofuels, bioplastics, other biochemicals and natural rubber), wood, and paper, encompassing the AFOLU sector and energy supply for biomass production, termed the global biomass carbon footprint[20]. We use the highly-resolved global MRIO database Resolved EXIOBASE version 3 (REX3)[3,19,27,41,42], which delineates between 189 countries and 163 sectors, and the time span from 1995 to 2022. We integrate LULUCF emissions from the Bookkeeping of Land Use Emissions (BLUE) model[7,43], other GHGs from AFOLU (mainly biogenic $CH_4$ and $N_2O$ emissions from enteric fermentation, rice cultivation, and fertilizer application), and GHGs from the biomass-related energy supply (e.g., for fertilizer production, biomass processing, and transportation). Our methodology prevents double counting and links biomass resources to their downstream end-uses for provisioning systems[20], building on the framework introduced in a recent UNEP report[3] that linked resources end-uses to provisioning systems. We extend this approach by connecting specific biomass products to their end-uses, such as nutrition (via food stores, restaurants, and canteens), energy and mobility (e.g., biofuels), the built environment (e.g., wood), and other provisioning systems (e.g., textiles for clothing, paper for education, and biochemicals for healthcare services). Finally, a marginal allocation is applied to link changes in GHG emissions in the bioeconomy supply chain to shifts in supply and demand for understanding the drivers of increases and decreases in GHGs[40]. The main objective of our study is to contribute to a comprehensive understanding of the complex linkages and flows of GHGs in the global bioeconomy supply chain by addressing three research questions (RQ):

RQ 1) Which regions are key exporters and importers of biomass goods?

RQ 2) Which goods and emission sources drive changes in consumption-based footprints in key importing regions?

RQ 3) What are the provisioning systems and supply chain hotspots for those goods that play a key role for mitigating GHGs?

## Results

### International trade in biomass products

Figure 1 illustrates the supply chain of the global biomass carbon footprint, reaching 19.0 Gt $CO_2$-eq in 2022. The footprint includes GHG emissions from LULUCF (29%), other AFOLU (42%), and energy supply (29%, see Supplementary Notes 2–4 and Supplementary Fig. 1 for an interpretation of the results of GHGs per emission source). In 2022, 29% of the global biomass carbon footprint was embodied in trade among the eleven world regions (Fig. 1c, d, colored flows), with an additional 7% attributed to intra-regional trade (results not separately shown here), meaning that 36% of the biomass carbon footprint is embodied in international trade. China, Europe, USA, and Middle East are key importers of biomass goods, while Brazil, Latin America, Southeast Asia + Pacific, and Africa are key exporters. For example, over half of Southeast Asia + Pacific's domestic biomass carbon footprint is linked to exports, while half of the consumption-based footprint in the Middle East, Europe, and the USA is from imports (Fig. 1c, d). China's imports contribute strongest to GHGs in Southeast Asia + Pacific and Brazil, while imports to the Middle East and Europe have the greatest impact in Africa. Similarly, the USA's imports contribute strongest to GHGs in Mexico and Canada.

Figure 2 illustrates the temporal changes in the global biomass carbon footprint, with the top row showing total GHGs and the bottom row displaying GHGs embedded in trade across eleven world regions. From 1995 to 2022, the global biomass carbon footprint has increased by 3.30 Gt $CO_2$-eq (+21%), with two-thirds of this increase (2.24 Gt $CO_2$-eq) attributed to rising international trade among the eleven regions (Fig. 2, bottom row), and another 12% (0.40 Gt $CO_2$-eq) attributed to rising intra-regional trade (results not separately shown here). This means that 80% of the rising biomass carbon footprint is attributed to rising international trade. Despite reduced domestic LULUCF emissions, Brazil's exported biomass carbon footprint has quadrupled since 1995, driven by beef and oilseed exports to China and the Middle East (see interactive version of Fig. 2), which show the strongest increase in imported GHGs. Since 1995, China's and the Middle East's imported biomass carbon footprints have increased fivefold and fourfold, respectively (Fig. 2d, bottom row). Consequently, China has shifted from a net exporter to a net importer, with more GHGs now linked to its consumption rather than its production of biomass products.

Using marginal allocation[39,40], Fig. 3 highlights shifts in the international trade of the global bioeconomy supply chain, linking regions where GHG emissions are rising or falling to regions where biomass goods are increasingly or decreasingly consumed due to trade. The figure shows that the net increase of 2.24 Gt $CO_2$-eq, referred to as 100% in the following, results from both gains (+3.36 Gt $CO_2$-eq, +150%) and reductions (−1.12 Gt $CO_2$-eq, -50%) in GHGs embodied in trade. Notably, 80% of the rising carbon footprint in trade is driven by increased imports from China (43%), the Middle East (24%), and the USA (9%) (Fig. 3b, summing positive and negative values). More than half of this increase is attributed to China's imports from Southeast Asia and the Pacific (17%) and Brazil (9%), the Middle East's imports from Africa (10%) and Brazil (5%), and the USA's imports from Latin America and Canada (10%). In contrast, the USA has decreased its imports of vegetables, fruits, and nuts from China. The associated lower LULUCF-related GHGs in China contributed to a 9% reduction in GHGs embodied in global trade. Similarly, Europe's carbon footprint from African imports (vegetables, fruits, nuts, and wheat) and Northwest Asia's wood imports from Southeast Asia and the Pacific are associated with additional reductions (−8% and −6%, respectively, Fig. 3). Among the goods consumed, over half of the rising carbon footprint in trade is linked to increased trade in beef (31%), biochemicals (17%), and textiles (10%), primarily consumed by China (beef, biochemicals, textiles), the Middle East (beef), the USA (beef, textiles, biochemicals), and Europe (textiles, biochemicals).

### Consumption-based impacts of key importing regions

Figure 4 provides an in-depth assessment of the shifts in the supply chain for the consumption-based biomass carbon footprint of China and the Middle East since 1995, connecting changes in supply and demand with corresponding increases or decreases in GHG emissions using a marginal allocation[39,40]. In China, shifts in supply chains are linked to considerable increases (1.90 Gt $CO_2$-eq, 189%) and decreases (–0.88 Gt $CO_2$-eq, –89%) in its consumption-based biomass carbon footprint, resulting in a net increase of 1.02 Gt $CO_2$-eq referred to as 100% in Fig. 4 (top). Over 70% of this net increase is driven by rising GHG emissions from energy supply, particularly coal, used mainly in the processing of biochemicals, textiles, and paper within China. As a result, non-food products have been the largest contributors to China's growing carbon footprint: biochemicals (26%), textiles (22%), and paper (13%) together account for more than 60% of the net increase in China's consumption-based biomass carbon footprint since 1995. Conversely, decreased domestic LULUCF emissions associated with the consumption of dairy products, beef, other foods, and wood have led to a

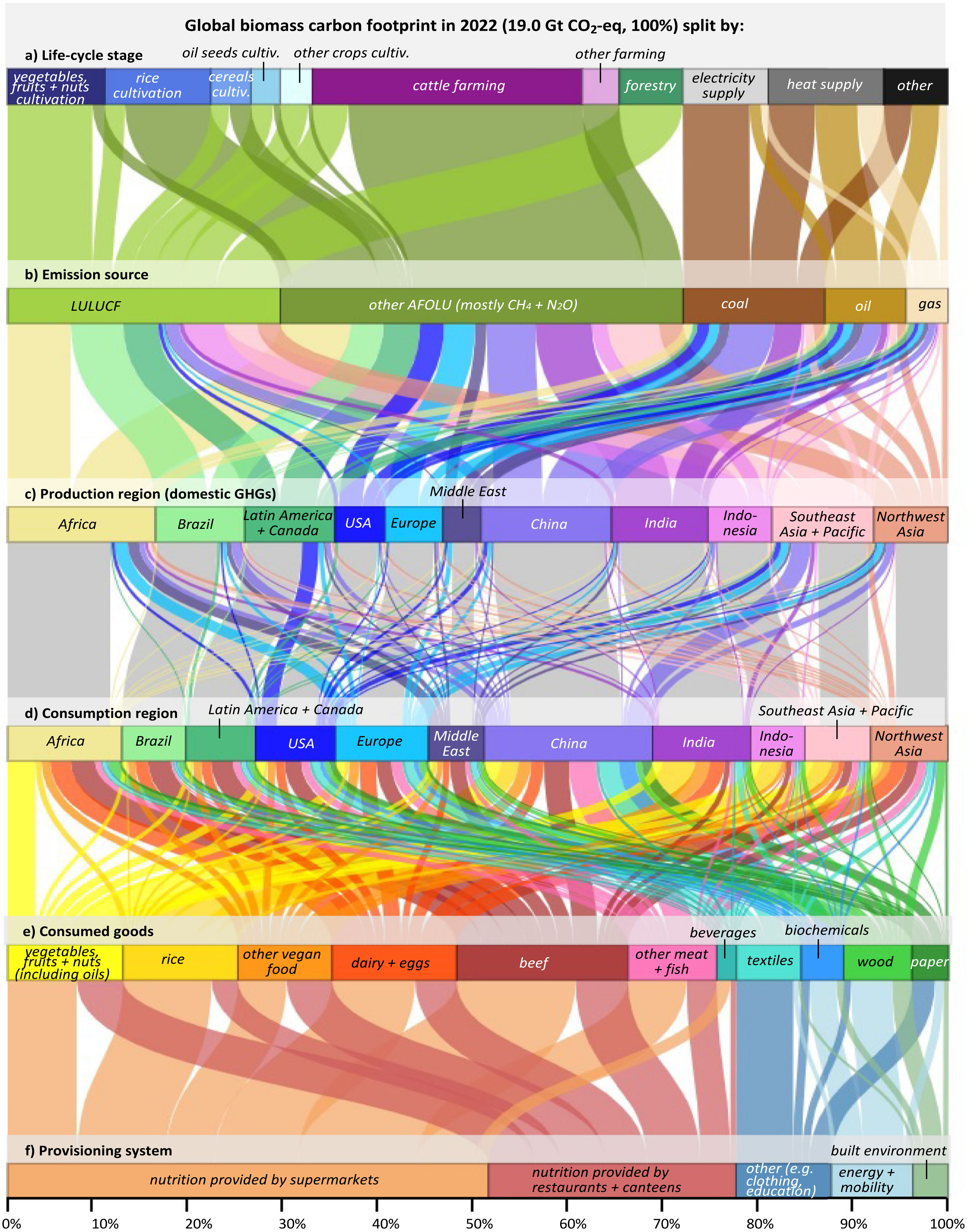


**Fig. 1 | Supply chain analysis of the global biomass carbon footprint in 2022.** The sum of each horizontal bar of the flow chart refers to the biomass carbon footprint in 2022 (19.0 Gt $CO_2$-eq, 100%) and allocates it to the different perspectives in the global supply chain: **a** the life-cycle stage, **b** the source of emissions, **c** the region of production, **d** consumption (footprint), **e** the consumed goods, and **f** the provisioning systems. The flows between the horizontal bars show the linkages within the global bioeconomy supply chain. Colored flows between production and consumption regions (**c**, **d**) represent international trade among eleven regions, while gray flows indicate intra-regional trade as well as domestic production and consumption. An interactive version enables a detailed assessment of GHG dynamics in the global bioeconomy supply chain from 1995 to 2022. The regional aggregation of countries is illustrated in the Supplementary Fig. 8.

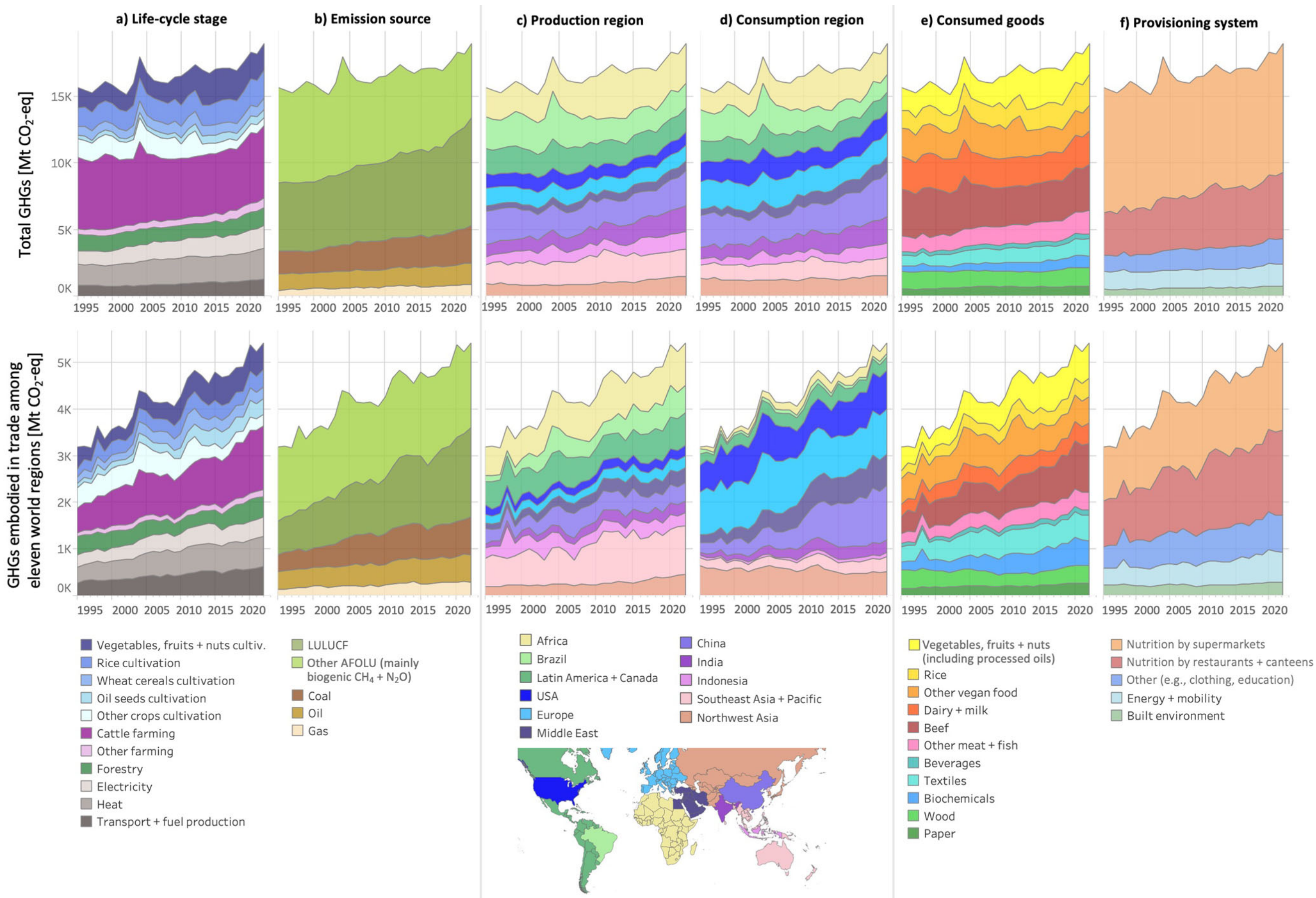


**Fig. 2 | Temporal evolution of the annual global biomass carbon footprint from 1995 to 2022 and role of international trade.** Upper figure: Total biomass carbon footprint. Lower figure: GHGs embodied in international trade among eleven world regions. GHGs embodied in intra-regional trade (e.g., GHGs embodied in Germany's imports from Spain) and the consumption of domestically produced goods are excluded in the lower Figure. GHGs are shown from six different perspectives within the global supply chain: **a** the life-cycle stage, **b** the source of emissions, **c** the region of production, **d**) consumption (footprint), **e**) the consumed goods, and f) the provisioning systems. Note that the scales of the y-axis differ in the upper and lower figure. Detailed insights on the intricate linkages and flows within the global bioeconomy supply chain are provided by an interactive version of Figure 2, which allows to recreate all results presented in the study.

72% decrease in China's biomass carbon footprint. This decrease was compensated by increased LULUCF and other AFOLU emissions related to China's increased consumption of imported goods (72%, Fig. 4, top), primarily beef and feedstock for biochemicals from Brazil and Southeast Asia. Notably, China's carbon footprint from importing Brazilian feedstock for biochemicals and beef has surged by over 100 and 30 times since 1995, respectively (Fig. 2), especially following a Strategic Partnership between China and Brazil in 2012 that strongly boosted trade in these commodities[44].

In the Middle East, shifts in the supply chain are related to increases (0.741 Gt $CO_2$-eq) and only small decreases (−0.0674 Gt $CO_2$-eq) in its consumption-based biomass carbon footprint, resulting in a net increase of 0.674 Gt $CO_2$-eq referred to as 100% in Fig. 4 (bottom). A third of this increase is attributed to rising energy supply, especially coal, mostly released domestically for processing textiles, wood, and food, while the main driver of Middle East's biomass carbon footprint was rising imports: 76% of the Middle East's rising biomass carbon footprint is attributed to rising imports, mainly biogenic $CH_4 + N_2O$ and LULUCF-related GHGs from beef imports sourced from Africa and Brazil (Fig. 4, bottom). Notably, the Middle East's carbon footprint related to beef and dairy imported from Africa has increased by more than 30 and 10 times respectively, mainly due to increased imports by Egypt and Oman from Nigeria, Ethiopia, and Kenya (Fig. 2). Furthermore, the Middle East's carbon footprint from Brazilian beef imports has increased over 60-fold since 1995. This is attributed to stronger economic partnerships, preferential trade agreements, and tariff reductions[45], such as the Brazil-Egypt Free Trade Agreement[46] and the Brazil-Saudi Arabia Economic Cooperation Agreement[47]. The provision of halal-certified meat by Brazil and African countries also accommodates the dietary preferences of the Middle East[48].

Further results for consumption-based biomass carbon footprints of the USA and Europe are illustrated in Supplementary Fig. 2 and interpreted in Supplementary Notes 5.

## Provisioning systems and key goods for GHG mitigation

Food provisioning contributes the most to the biomass carbon footprint globally and regionally (Fig. 1d–f). More than half of the global food carbon footprint is related to animal products, though the contribution of animal products varies considerably by region. In Brazil, two-thirds of the food carbon footprint is attributed to animal products, mainly beef from domestic cattle farming. Despite a decline in LULUCF emissions in Brazil since 2004, the per-capita carbon footprint of Brazilian beef consumption remains higher than the per-capita biomass carbon footprints of Africa, China, India, and Southeast Asia + Pacific in 2022 (Supplementary Fig. 5). Conversely, animal-based food products account for less than 20% of India's biomass carbon footprint, reflecting a stronger reliance on plant-based diets (Fig. 1d–f). However, India faces high malnutrition challenges, underscoring the need for efforts to promote healthy and sustainable diets[49].

Among provisioning systems, nutrition provided by restaurants and canteens has contributed to more than half of the increase in the biomass carbon footprint (Fig. 2). This trend is largely driven by the global increase in dining out, fueled by urbanization and rising incomes[50]. China and the

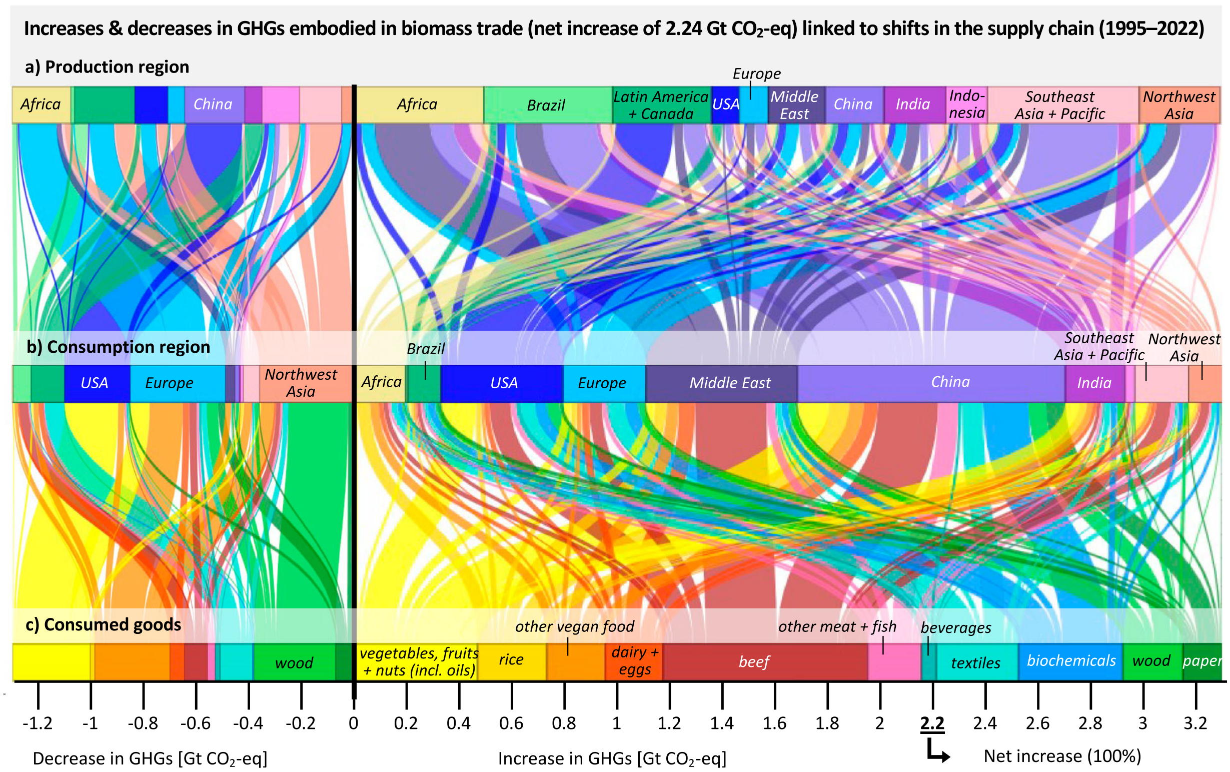


**Fig. 3 | Increases and decreases in the global biomass carbon footprint embodied in international trade among eleven world regions from 1995 to 2022.** The resulting net increase of 2.24 Gt $CO_2$-eq, which is referred to as 100% in the text, is linked to shifts in the global supply chain including the perspectives of international trade among regions of production and consumption (**a**, **b**), and the consumption of imported goods (**b**, **c**). The color code of the labels is the same for the left and the right side of the figure. The regional aggregation of countries is illustrated in the Supplementary Fig. 8.

Middle East together contributed to over 50% of this increase, primarily through consumption of animal-based foods. In 2024, two-thirds of global nutrition was provided by food stores, with the remaining one-third taking place in restaurants and canteens (Fig. 1e, f). As only 10–15% of global calories are supplied by restaurants and canteens, their average global per-calorie carbon footprint is about three times higher than that of food sold through food stores. This disparity is partly due to the higher prevalence of eating out in wealthier regions[50], where consumption of meat and other high-impact foods is more common. Additionally, restaurants and canteens tend to rely more heavily on imported foods: in 2022, over half of the carbon footprint associated with traded food was linked to consumption in restaurants and canteens (Fig. 2). The impact is most notable for African beef exports: over 80% of African beef imported by Europe and the Middle East is consumed in restaurants and canteens. This trend may be due to less stringent food labeling regulations compared to food stores[51], the demand for quality and specialty cuts, ethnic cuisine, halal food markets, and other customer preferences[52–54]. These factors underscore the critical role restaurants and canteens play in the distribution and environmental impact of traded food.

Non-food products including wood, paper, textiles, and biochemicals contribute to more than 20% of the global bioeconomy's footprint in 2022, and to almost 40% of the rise in the bioeconomy's carbon footprint (Fig. 2). Key drivers include energy-intensive production processes and a shift to coal-based energy for textiles, biochemicals, and paper production especially in China and the Middle East (textiles), as well as rising LULUCF emissions in Brazil and Southeast Asia to extract feedstock for biochemicals. Biochemicals show the largest relative increase in total carbon footprints (Fig. 2e): Since 1995, the biochemicals' carbon footprint has doubled, reaching 0.871 Gt $CO_2$-eq in 2022. Biochemicals also show the highest reliance on international trade, followed by textiles (Supplementary Fig. 3): In 2022, over 60% of the biochemical's carbon footprint and almost 50% of the textile's carbon footprint is embodied in international trade.

Due to the importance of biochemicals for mitigating future GHG emissions, we provide an in-depth analysis specifically for GHGs in the biochemicals supply chain in Fig. 5, which include biofuels for energy, bioplastics for packaging and construction, and rubber for transportation (Fig. 5d–e). Nearly 50% of the biochemicals' carbon footprint is from energy provision, mostly fuel combustion for processing, and about 40% is from LULUCF-related GHGs during feedstock cultivation (Fig. 5a, b). Most GHGs from feedstock extraction occur in Brazil, Indonesia, and Malaysia, while processing emissions occur mainly in China from coal combustion (Fig. 5a–c). China, Europe, and the USA are key importers of GHGs embodied in biochemicals (Fig. 5c, d). In 2022, more than 80% of Europe's carbon footprint from biochemicals was induced abroad. China's consumption has contributed the most to the rising carbon footprint of biochemicals. Since 1995, China's carbon footprint from biochemicals has more than quadrupled, making up more than half of the increase in the global carbon footprint of biochemicals (Supplementary Fig. 4). Two-thirds of the biochemicals carbon footprint is attributed to biofuels and other biochemicals production (e.g., bio-based solvents, surfactants, lubricants, additives, and pharmaceuticals), while a third is attributed to bioplastics and natural rubber production (see interactive data visualizer with distinction for biochemicals for further in-depth results).

## Discussion

This study provides a comprehensive assessment of GHGs related to biomass extraction and processing, identifying hotspots and drivers in the global bioeconomy supply chain from 1995 to 2022 (Fig. 2). Using the multi-regional input-output database REX3, we achieve high regional, sectoral, and temporal resolution. Our approach traces the entire upstream and downstream biomass supply chain, preventing double counting, and incorporates marginal allocation to link changes in GHG emissions with

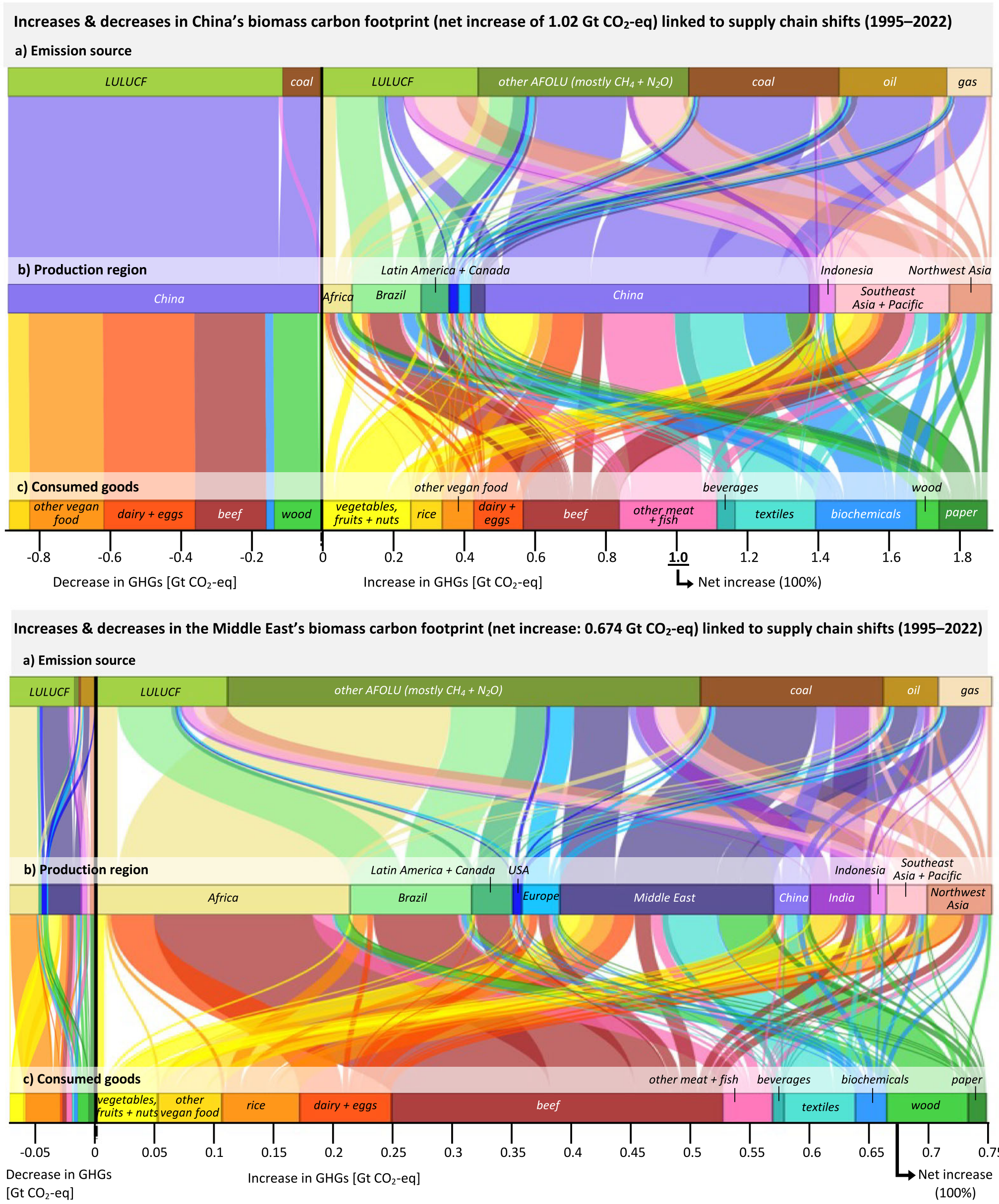


**Fig. 4 | Increases and decreases in the consumption-based biomass carbon footprint of China and the Middle East from 1995 to 2022.** The resulting net increase of 1.02 Gt $CO_2$-eq for China and 0.674 Gt $CO_2$-eq for the Middle East, referred to as 100% in the text, respectively, is linked to shifts in the global supply chain including the perspectives of emissions source by production region (**a**, **b**) and consumed goods (**b**, **c**). The color code of the labels is the same for the left and the right sides of the figures. The regional aggregation of countries is illustrated in the Supplementary Fig. 8.

shifts in the bioeconomy (Figs. 3 and 4). While no comparable assessment of GHG emissions across the entire bioeconomy supply chain exists, we compare our findings to previous studies on food[23,33,55], agricultural products[10,56,57], and biochemicals[58,59] to showcase the improvements in our approach. These comparisons help explain discrepancies with previously reported values and highlight the enhanced precision and scope of our method:

### Full supply chain coverage

We find that more than 36% of the global bioeconomy's carbon footprint in 2022 is linked to international trade, which is 50% higher than previous studies on food systems that reported trade contributions of 22–26%[10,33,56]. This increase is not only due to the inclusion of non-food products like biochemicals and textiles, which heavily rely on international trade (Supplementary Fig. 3), but also reflects methodological differences. For example, Pinero et al.[56] focus on impacts embodied in direct trade relations, while Li et al.[33] apply a physical trade flow approach. Our approach[20] offers a more comprehensive mapping of both GHGs associated with upstream activities (e.g., coal used in biomass processing) and downstream uses of biomass products until their final consumption by provisioning systems (Fig. 1). This enhanced methodology likely also explains why we find that 80% of the increase in the bioeconomy's carbon footprint is attributable to rising international trade—a figure over 50% higher than previous estimates for food between 2000 and 2019[33].

### Inclusion of regionalized energy supply

The carbon footprint of agri-food products (15.2 Gt $CO_2$-eq in 2013) is higher than that reported by Pinero et al.[56] (13.0 Gt $CO_2$-eq in 2013). This discrepancy may be attributed to the regionalized energy mix for processing agri-food products, thereby accounting for the increased reliance on coal

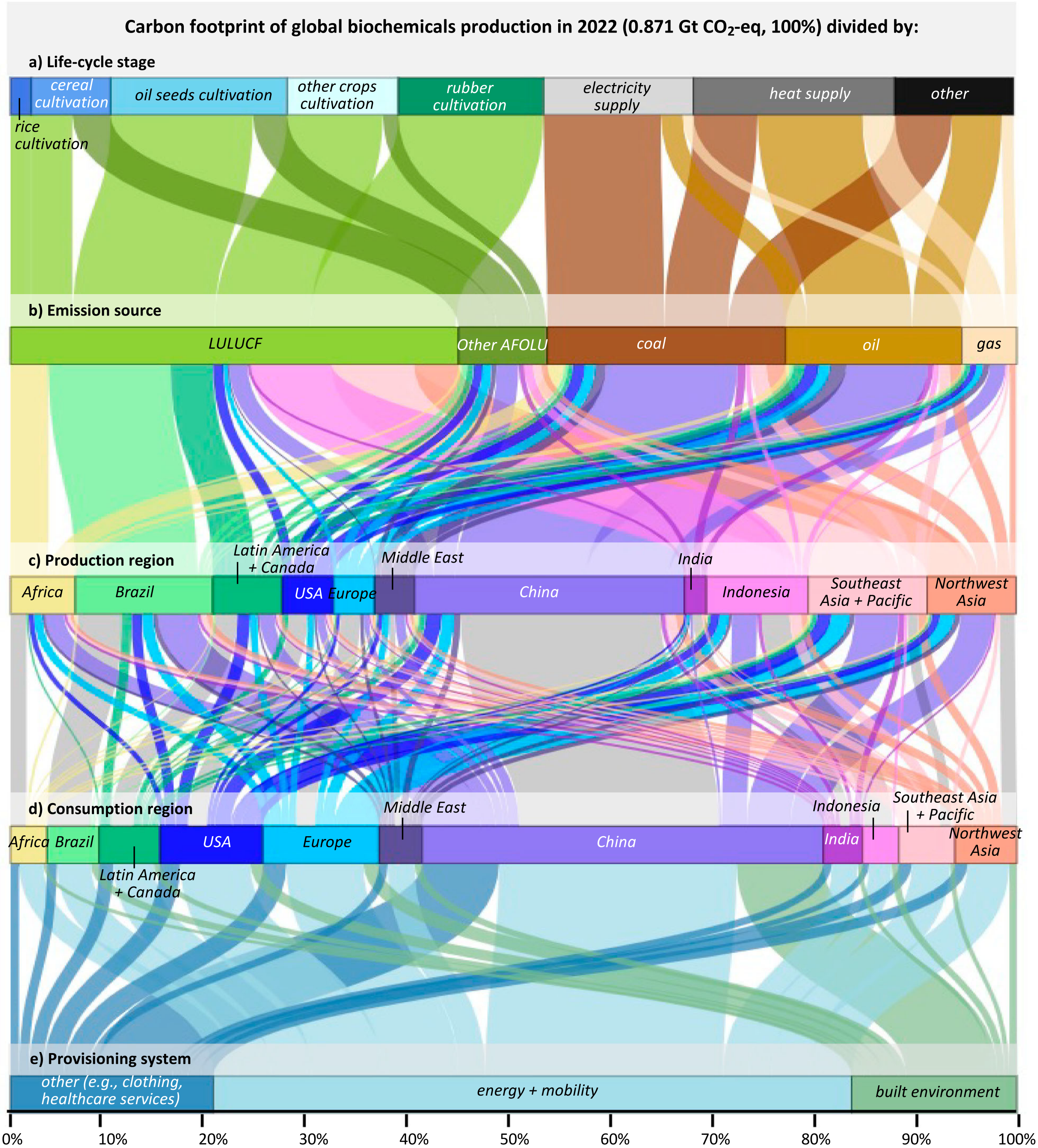


**Fig. 5 | Supply chain analysis of the global biochemicals carbon footprint in 2022.** The sum of each horizontal bar of the flow chart refers to the biochemicals carbon footprint in 2022 (0.871 Gt $CO_2$-eq, 100%) and allocates it to the different perspectives in the global supply chain: **a** the life-cycle stage, **b** the source of emissions, **c** the region of production, **d** consumption (footprint), and **e** the provisioning systems. The flows between the horizontal bars show the linkages within the global biochemical supply chain. Colored flows between production and consumption regions (**c**, **d**) represent international trade among eleven regions, while gray flows indicate intra-regional trade as well as domestic production and consumption. The regional aggregation of countries is illustrated in Supplementary Fig. 8. Separate results for bioplastics and natural rubber, as well as biofuels and other biochemicals are illustrated in an interactive data visualizer.

combustion in biomass processing, particularly in China, India, and the Middle East, which was not distinguished in Pinero et al.[56], but is considerable. For instance, over half of the paper carbon footprint and over 40% of the textile carbon footprint come from coal combustion in 2022 (Fig. 2).

### Inclusion of LULUCF and food services

The food carbon footprint (13.2 Gt $CO_2$-eq in 2011) is two times higher compared to Wood et al.[19,23] (6.2 Gt $CO_2$-eq in 2011). This discrepancy arises from our incorporation of LULUCF, contributing 29% to the global food carbon footprint (Fig. 2). Additionally, our methodology[20] accounts for GHGs of food consumed in restaurants and canteens, constituting one-third of the global food carbon footprint (Fig. 1f). In the standard Leontief model[17] applied by Wood et al.[23], these emissions are not allocated to food, but to the respective end-use sectors (e.g., GHGs from food consumed in canteens within the construction sector are allocated to the construction sector).

### Double counting prevention

The food carbon footprint found here (13.1 Gt $CO_2$-eq in 2010) is slightly lower than the bottom-up estimates from Poore and Nemecek[57] (13.7 Gt $CO_2$-eq in 2010) and considerably lower than that by Xu et al.[55] (17.5 Gt $CO_2$-eq in 2010). This discrepancy may result from our cradle-to-gate perspective, while Poore and Nemecek[57] adopted a cradle-to-grave perspective, including transport to end-consumer and GHGs from retail and restaurants (e.g., cooking energy). Additionally, our approach prevents double counting[20,21], which might have led to overestimation in those bottom-up studies. However, similar to Xu et al.[55], we find that the global carbon footprint of animal-based food is twice that of plant-based food.

### Inclusion of biochemicals

The carbon footprint of biochemicals found here (871 Mt $CO_2$-eq in 2022) is higher compared to bottom-up LCA estimates[58] despite potential double counting in these studies. In these studies, the carbon footprint was found to range between 1.5–4 t $CO_2$-eq/t biochemicals—multiplied with the global production of bio-based chemicals (~90 to 150 million metric tons per year), this results in a lower carbon footprint ranging from 120-600 Mt $CO_2$-eq. The reason for the higher biochemical carbon footprint found here is that we also include LULUCF emissions. These emissions are excluded in previous LCA assessments of biochemicals[58,59], but are essential (43% of the biochemicals carbon footprint, Fig. 5), as the feedstock for biochemicals production is mainly extracted in regions with high deforestation rates. Another reason for the higher biochemicals carbon footprint found here is that ref. 58 calculated with the USA's electricity mix, while our study takes the specific electricity mixes of all regions into account, whereby the carbon footprint is dominated by Chinese coal energy to supply biochemicals to the global market (Fig. 5).

Our approach to map the bioeconomy supply chain[20,40], in conjunction with the REX3 database[42], enables in-depth assessments of 38 biomass sectors of 189 countries, supporting sustainability policies in the global bioeconomy (Fig. 2, Supplementary Tables 1, 2). However, several limitations require consideration and future research:

### Temporal resolution

REX3 incorporates modeled LULUCF emissions up to 2021, reported GHG data and macro-economic accounts up to 2019, as well as bilateral trade data up to 2021[60], while subsequent data until 2022 are extrapolated[61]. Going forward, future work should incorporate reported data reflecting recent trends[62], including impacts of the COVID-19 pandemic[63] and recent geopolitical events[64]. Improved remote sensing data are also expected to improve LULUCF data, reducing uncertainties[7,65].

### Sectoral resolution

While REX3[42] facilitates mapping global economic linkages, it lacks the granular resolution in agri-food products compared to the FABIO[29] database, which covers these sectors in higher detail, but excludes other industries. Moreover, REX3 operates in monetary units, potentially underestimating the carbon footprint of crops used for feed due to their lower monetary value compared to those used for food and biochemicals. To capitalize on complementary strengths, future research should explore fully integrating the REX3 database[42] with FABIO[29]. Unlike previous approaches[56] that have merely soft-linked the downstream use of agri-food products, a more integrated approach involving a fully merged database[41,66] should be considered. Since MRIO databases[19,27,29,42] do not distinguish biochemicals but aggregate them with fossil-based plastics and chemicals, future work should disaggregate separate sectors for biofuels, bioplastics, rubber, and other biochemicals.

### Country resolution and data quality

REX3's spatial resolution is limited to the country-scale, with lower data quality for smaller economies or regions with less comprehensive reporting, especially those not separately represented in EXIOBASE3[19,41]. This increases uncertainty in consumption-based footprints for countries with low population and income. Combining top-down MRIO models with bottom-up approaches[67,68] could reduce these uncertainties and improve both sectoral and regional resolution.

### Homogeneity and linearity assumptions

MRIO analysis assumes that all outputs within a sector use the same technology and inputs (homogeneity) and that relationships between inputs and outputs are linear, which can oversimplify real-world complexities. Moreover, MRIO models are static and retrospective, limiting their use for scenario analysis. Combining MRIO with computable general equilibrium models[69–71], could address these limitations.

### Transportation and downstream emissions

This study underestimates GHGs from biomass transportation, which accounts for 3–6% of the carbon footprint of food[57,72,73], and as much as 19% in a recent study on food transport[74] that also included related cooling, transport of machinery, fertilizers, and other inputs. Additionally, GHGs from cooking, heating, and cooling food[57], currently not separately reported in MRIO databases[19,42], should be differentiated. Future research should integrate these emissions utilizing the ecoinvent database[75] for greater accuracy.

### Provisioning systems

While we link specific biomass products and related GHGs to their end-uses within provisioning systems[3,20], our MRIO approach does not differentiate between basic and non-basic human needs. Future research should investigate how to meet basic needs while staying within planetary limits[2], building on previous work[76–78].

### Policy Implications

We found that nearly 80% of the bioeconomy's growing carbon footprint is driven by increased international trade in biomass products, with China, the Middle East, and the USA being the largest importers, while Brazil, Latin America, Southeast Asia + Pacific, and Africa are key exporters. Beef and biochemicals were the most important contributors among imported goods, while food provision by restaurants and canteens had the highest impact among provisioning systems, fueling the rise in both total and trade-related emissions (Fig. 2). These results highlight the importance of extending current policy frameworks[11–13] to a consumption perspective to foster sustainable sourcing strategies along the entire bioeconomy supply chain. A notable regulatory action is the European Union's EU Deforestation Regulation enacted in 2023[79], which bans the import of food and wood products from deforested tropical areas and aims to establish strong audit and traceability mechanisms. Additionally, the EU Supply Chain Act[80], passed by the European Parliament in 2024, strengthens environmental protection within global supply chains by holding large companies accountable for identifying, preventing, and mitigating environmental risks throughout their supply networks. Another example is food and textile labeling regulations in food stores and apparel stores[51]. Such policies are pivotal steps forward, but need to take transnational leakage into account[81]. Therefore, it is critical to expand these measures i) beyond Europe to major importers such as China, the Middle East, and the USA, ii) across all biomass goods including also biochemicals, and iii) across all provisioning systems, particularly restaurants and canteens.

While biochemicals play a key role in tackling climate goals, this study also shows that biochemicals show the strongest relative increase in GHG emissions, driven mainly by China's consumption. The high fraction embodied in trade (>60%) and high LULUCFs emissions further highlight the importance of enhanced land conservation in combination with sustainable sourcing strategies: The cultivation of bio-based feedstock on undisturbed land would reduce the carbon footprint of biochemicals by up to 43% (Fig. 5). Moreover, our results highlight the high leverage for reducing the combustion-related carbon footprint of biochemicals production by switching to renewables, as the main contributor of the chemicals industry's GHGs is the energy provision, especially Chinese coal energy, and not the feedstock[14,82]. Our findings show that shifting to renewable energy could reduce combustion-related GHGs by more than 50% for biochemicals, more than 80% for textiles, and by nearly 30% for the entire biomass carbon footprint (Fig. 1b). However, transitioning to renewables would also lead to an expansion of cropland and/or forestry to meet increased bioenergy demand, which, in turn, would raise GHGs due to the considerable contribution of LULUCF emissions (Fig. 5). This underscores the need for integrated strategies that promote the adoption of renewables while mitigating LULUCF emissions, which could reduce the bioeconomy carbon footprint by nearly 60% (Fig. 1).

In this study, biochemicals include biofuels, bioplastics, other biochemicals, and natural rubber. While the limited product resolution in MRIO prevents us from isolating the carbon footprint of each sub-group, we can distinguish between bioplastics and natural rubber (33% of GHGs), as well as biofuels and other biochemicals (67% of GHGs; see extended interactive data visualizer). With bioplastics and natural rubber representing ~25% of the market share[83,84], their average carbon intensity (GHGs per euro of output) is therefore slightly higher than that of biofuels and other biochemicals (~75% market share)[85,86]. The difference is far more pronounced per mass of product, with bioplastics and natural rubber accounting for only ~5%[84,87] compared to ~95% for biofuels and other biochemicals[86,88]. As a result, the average carbon intensity (GHGs per mass of output) is considerably higher for bioplastics and natural rubber than for biofuels and other biochemicals. This disparity is likely due to more energy-intensive and complex production processes (e.g., polymerization, purification)[89], the high carbon intensity of specific inputs like stabilizers, chemical additives, and fossil-derived materials[90], and lower yield efficiency for bioplastics and, to some extent, natural rubber[91]. For instance, producing 1 ton of bioplastics requires more feedstock than producing 1 ton of biofuels like bioethanol[91]. Further research is essential to provide a more detailed assessment of GHG emissions in the global supply chains of bioplastics, natural rubber, biofuels, and other biochemicals in comparison to their production volumes.

Consistent with previous studies on food systems[10,33,55–57], we find that rising meat consumption, primarily driven by affluence, is a major contributor to the carbon footprint of the entire bioeconomy. Furthermore, we emphasize the important role of restaurants and canteens in the distribution of these carbon-intensive foods, particularly in regions like China and the Middle East. These regions have been the strongest contributors to the rising carbon footprint of restaurants and canteens, fueled by rising urbanization and incomes[50]. Despite these trends, per-capita biomass carbon footprints remain higher in the USA and Europe (Supplementary Fig. 5). Therefore, a shift towards more plant-based diets[5] is crucial and could achieve a 50% reduction in the food carbon footprint[92,93]. To facilitate these transitions, implementing economic incentives such as carbon taxes[94–96] and eliminating subsidies for carbon-intensive products such as animal-based foods[97]. This is crucial since regions with high projections in population growth (e.g., Africa and Southeast Asia) are likely to replicate the consumption patterns of wealthier regions (Supplementary Fig. 5). Additionally, it is vital to address rising carbon footprints driven by affluence[78] through fostering consumer awareness and sustainable lifestyle changes[98]. These measures are indispensable for addressing the dual climate and biodiversity crisis, given the considerable impact of the global bioeconomy[3,5,40]. This study's approach[20] and dataset[42] highlight the interconnectedness of the global bioeconomy's supply chain and emphasize the need for coordinated international efforts to meet climate and biodiversity targets.

## Methods

### Resolved EXIOBASE version 3 (REX3)

Various global multi-regional input-output (MRIO) databases exist[19,27–32], differing in regional, sectoral, and temporal resolution. We utilized the Resolved EXIOBASE3 database version 3 (REX3)[3,40–42], which covers 189 countries, 163 sectors, and the time span from 1995 to 2022. REX3 is built on EXIOBASE3[19,27] (version 3.8.2), which aggregates the global economy into 44 countries and five rest-of-the-world regions. REX3 extends the spatial resolution to 189 individual countries by integrating data from Eora26[28] while maintaining the high sectoral resolution of EXIOBASE3. Additionally, REX3 incorporates production data from FAOSTAT and bilateral trade data from the BACI database[60] for all biomass sectors, including crops, animal farming, forestry, and the processing of food, textiles, paper, and wood. REX3 is provided open-access[40,42], and further described in Supplementary Notes 6, while earlier versions are described in refs. 41,66.

Using the Global Warming Potentials for 100 years (GWP100) from IPCC[99], we included three categories of GHGs in REX3, measured in $CO_2$-equivalents ($CO_2$-eq). The first category covers $CO_2$ emissions from land use, land-use change, and forestry (LULUCF). The second category encompasses biogenic $CH_4$ and $N_2O$ emissions from agriculture, forestry, and other land use (AFOLU), including emissions from enteric fermentation, rice cultivation, manure management, synthetic fertilizer application, and $CO_2$ from peat decomposition. This study refers to this category as "biogenic $CH_4$ and $N_2O$ emissions," as $CO_2$ from peat decay is minimal (<1%). The third category includes GHGs from energy supply used in biomass production, mainly $CO_2$ from fuel combustion and $CH_4$ from fossil fuel extraction. $CO_2$ emissions from biomass combustion are excluded in line with IPCC[99] guidelines, because of the assumption of re-sequestration by biomass regrowth. However, this approach is debated due to the time gap between $CO_2$ release and re-sequestration for slow-growing biomass and its warming effect[100].

### LULUCF emissions

For LULUCF emissions, we used data from the spatially explicit BLUE model by Hansis et al.[43], covering 1995 to 2021 at a 0.25° resolution (~28 km)[7], with 2021 data also applied to 2022. The BLUE model, extensively used for quantifying LULUCF-related carbon fluxes, informs global[7,9,10] and country-level[101,102] land use, management, and mitigation policies, including those by the IPCC[5]. It accounts for deforestation, afforestation, forest management, and agricultural practices to calculate $CO_2$ emissions and removals from land-use changes and management. This includes the conversion of natural land to cropland and pastures, the abandonment of cropland and pastures, the degradation from primary to secondary land through the use of natural vegetation as rangeland, the decay of harvested wood products and biomass left on-site after harvest, and vegetation regrowth after wood harvest.

We allocated $CO_2$ emissions from deforestation to agriculture, the primary driver of land-use change emissions, rather than to wood, considered a by-product[40,103]. Conversely, wood harvest predominantly drives changes in carbon stock in forests (both living biomass and soil), while cropland and pasture management cause relatively minor changes. We also considered carbon emissions from peatland fires and drainage based on modeled and observed data[7], allocating these emissions to cropland and pastures, as peatland is usually converted for agricultural purposes. For example, if 80% of the change in agricultural land in Indonesia from 2021 to 2022 was due to cropland, 80% of the peatland emissions were allocated to Indonesia's cropland sector. Carbon removals from the abandonment of cropland and pastures, presented as a single flux in BLUE (without distinction between cropland and pastures), were proportionally allocated based on carbon fluxes from the conversion of natural land to these uses.

We calculated net LULUCF-induced carbon fluxes for cropland, animal farming, and forestry per country and year. For cropland, this involved combining carbon fluxes from land conversion to cropland expansion, peatland conversion to cropland, and cropland abandonment. For animal farming, we aggregated carbon emissions from the conversion of natural land to pastures, peatland conversion to pastures, carbon removals from pasture abandonment, and emissions from land degradation due to rangeland use. For forestry, the net carbon flux included $CO_2$ emissions from the decay of harvested wood products and on-site biomass, and carbon removals from vegetation regrowth after wood harvest. Negative net values were set to zero to avoid negative emissions in REX3, resulting in slightly higher global LULUCF emissions compared to the BLUE model (4–10% globally, depending on the year, Supplementary Fig. 6). These differences are mainly attributed to negative LULUCF emissions of cropland abandonment in Europe, the USA (1995–2019), and Northwest Asia (1995–2010, Supplementary Fig. 7).

Net carbon fluxes for cropland were allocated to eight crop cultivation sectors in REX3, proportional to changes in cropland area per country and year. For example, if 20% of cropland area change in Brazil from 2021 to 2022 was due to oilseeds, 20% of Brazil's net LULUCF emissions for cropland were allocated to the oilseeds sector in REX3. As this method overlooks crop-specific land-use change patterns, future work should offer land-use change emissions for specific land transitions between different crop types by combining carbon budget models with remote sensing techniques and deep learning models[104]. Similarly, net carbon fluxes for animal farming were allocated to two cattle farming sectors (meat and dairy) based on respective land-use area changes. Net carbon fluxes for forestry were allocated to the forestry sector.

### Other AFOLU (biogenic $CH_4$ and $N_2O$)

Biogenic $CH_4$ and $N_2O$ emissions from EXIOBASE3, based on FAOSTAT, were converted to $CO_2$-equivalents using the IPCC-recommended Global Warming Potentials over 100 years (GWP100)[99] of 27 and 273, respectively. These emissions were combined with $CO_2$ emissions from peat decay to calculate the total $CO_2$-equivalents. To derive impact coefficients (kg $CO_2$-eq/Euro), total $CO_2$-equivalents were divided by the total output (in Euro) of each sector and region in EXIOBASE3. For the disaggregated 145 Rest-of-the-World countries, sector-specific impact coefficients from each EXIOBASE3 rest-of-world region were used. For instance, impact coefficients for biogenic $CH_4$ emissions from cattle farming in the rest-of-America region were applied to all cattle farming sectors within that region, such as Chile and Peru.

### Energy-related GHGs (coal, oil, gas)

For energy-related GHGs in biomass production, $CH_4$ emissions from fossil fuel extraction were converted to $CO_2$-equivalents using the IPCC-recommended[99] GWP100 of 29.8 and added to $CO_2$ emissions from fuel combustion. Impact coefficients (kg $CO_2$-eq/Euro) were derived by dividing the total $CO_2$-equivalents by the total output (in Euro) of each sector and region. Sector-specific impact coefficients from EXIOBASE3 were used for the disaggregated 145 rest-of-the-world countries. For example, impact coefficients for energy-related GHGs in beef processing within the rest-of-America region were uniformly applied across beef processing sectors in countries like Chile and Peru. Emissions from coal, oil, and gas used in biomass production were differentiated using fuel-specific contribution matrices as described in ref. 14.

### Supply chain analysis of the global biomass carbon footprint

To assess the global biomass carbon footprint without double counting covering the entire upstream and downstream chain of biomass products, we applied the supply chain impact mapping method from Cabernard et al.[20] based on Dente et al.[21], similar to prior studies on global material[20] and plastics production[14]. In addition to the perspectives of production and consumption of standard MRIO analysis[18,23–26], this approach adds an intermediate perspective to the global supply chain, and connects it in a multi-dimensional impact array (one dimension for each perspective). In our study, we constructed a six-dimensional impact array with the dimensions of $5 \times 164 \times 189 \times 189 \times 164 \times 5$ for each year from 1995 to 2022. The 1st dimension represents the emission sources, including LULUCF, other AFOLU (biogenic $CH_4$ and $N_2O$ emissions), as well as energy supply through coal, oil, and gas, respectively. The 2nd dimension corresponds to the producing sectors and households responsible for releasing GHGs, while the 3rd dimension refers to the producing countries where these GHGs are emitted. The 4th dimension encompasses the consuming countries, considering emissions related to imports while excluding exports. The 5th dimension captures the supply chain impacts of produced biomass goods (e.g., food, textiles, paper, wood, biochemicals), as well as the impacts of the remaining global economy and households. The 6th dimension corresponds to five provisioning system of final consumption, including nutrition provided by food stores and restaurants + canteens, energy + mobility, the built environment, and other provisioning systems (e.g., clothing and education).

The intermediate perspective represented in the 5th dimension is based on the principle of dividing the global economy into a target economy and a non-target economy[20,21]. Specifically, we considered sectors involved in the extraction and processing of biomass products, such as food, textiles, biochemicals, wood, and paper, as target-sectors (a total of 38 target sectors, Supplementary Table 1). All countries were considered target regions, resulting in 7182 target-sector-regions representing the global production of biomass products, and 23,625 non-target sector regions representing the remaining global economy (125 non-target sectors × 189 countries). The allocation of GHGs to target sector regions is based on the principle that, for instance, if crops are used to feed animals, produce textiles (e.g., cotton) or biochemicals (e.g., bioplastics), the GHGs of these crops are allocated to the produced commodities, respectively. However, if biochemicals like bioplastics are used for food packaging or textiles, their impacts are not counted again among food or textiles to prevent double counting. As a result, this procedure enables us to assess the full supply chain impacts of biomass products (target-sectors) without double counting, while also considering the impacts of the remaining global economy and households, which are stored in the 5th dimension of the impact array. In essence, the sum of the 6D-impact array equals the standard Leontief model while providing additional information on the linkages in the global supply chain, such as the bioeconomy.

As the REX3 database does not distinguish between biochemicals and other chemicals, we made additional assumptions. We considered LULUCF and other AFOLU ($CH_4 + N_2O$) emissions (1st dimension) related to crops cultivation (2nd dimension) used for chemicals (5th dimension). Since ~5–10% of global chemicals production is based on biomass feedstock[105], we allocated an average of 7.5% of the combustion-related GHGs of total chemicals production to biochemicals.

### Marginal allocation

Using the principle of marginal allocation[39,40], we linked changes in GHG emission to shifts in supply and demand of the global bioeconomy supply chain. This was done by subtracting the 6D-impact matrix from the year 1995 from the year 2022. The result is a matrix with the same dimension, but including both positive and negative values. These positive and negative values refer to changes in global supply chain dynamics that were driving increases and decreases in the global biomass carbon footprint, while the sum refers to the net change in the global biomass carbon footprint from 1995 to 2022. To examine the supply chain dynamics driving the changes in the global biomass carbon footprint embodied in international trade, we set all flows referring to the consumption of domestically produced goods to zero and aggregated the 1st, 2nd and 6th dimension of the 6D-impact array (Fig. 3). To evaluate the changes in the supply chain of the consumption-based biomass carbon footprint of China, the Middle East, the USA and Europe we selected the respective consumption region in the 4th dimension of the 6D-impact array while aggregating the 2th and 6th dimension (Fig. 4 and Supplementary Fig. 2).

### Provisioning systems

We build on the definition of provisioning system from Fanning et al.[36] applied in a UNEP report of the International Resource Panel[3] to link end-use of resources to provisioning systems. This approach ensures that resource usage and its associated impacts are attributed to the systems responsible for final consumption. For the global bioeconomy, we distinguish the provisioning systems of nutrition (provided by food stores, restaurants, and canteens), energy and mobility, the built environment, and other provisioning systems. Nutrition provided by food stores refers to the carbon footprint of food products directly consumed by the final demand. Nutrition provided by restaurants and canteens refers to the carbon footprint of food demanded by other sectors (e.g., restaurants and the education sector for university canteens) and hence indirectly consumed by the final demand via non-target sectors. Energy and mobility, as well as the built environment, refer to the carbon footprint of these provisioning systems from a consumption perspective due to the end-use of biomass goods (e.g., biofuels for energy, rubber for mobility, and wood for construction). Other provisioning systems include everything else (e.g., textiles for clothing, paper for education and communication, rubber and biopharmaceuticals in healthcare systems). For instance, the linkage between biomass products and the remaining economy (5th dimension) versus the built environment (6th dimension) indicates which fraction of the global carbon footprint of the built environment is related to the bioeconomy (e.g., wood), and which fraction is related to other sectors in the supply chain (e.g., steel and cement processing).

### Regional grouping

The 189 countries in the REX3 database were grouped into eleven regions for analysis (Supplementary Fig. 8). Countries that contribute more than 5% to the global biomass carbon footprint, either through production or consumption, were analyzed individually: Brazil, the USA, China, India, and Indonesia. The remaining countries were organized into six broader regions based on their trade behavior. These include Latin America + Canada and Southeast Asia + Pacific, which are net exporters of GHGs embodied in biomass products, and Europe and the Middle East, which are net importers. Additionally, Northwest Asia includes a mix of both net-exporting and net-importing countries for GHGs embodied in biomass goods. This categorization highlights the distinct roles these regions play in the global bioeconomy supply chain, particularly in terms of their trade dynamics and contributions to the embodied GHG emissions.

### Reporting summary

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

## Data availability

The source data of the figures are provided in a zenodo repository. Moreover, all results presented in this study can be recreated with an interactive data visualizer, which also allows to download all results as csv.files. Further in-depth results with distinction for biochemicals (bioplastics and natural rubber, biofuels and other biochemicals) are available here. Additional results presented in this study are illustrated and discussed in the Supplementary Information. The GHG data on LULUCF emissions and distinction of emission sources in REX3 are provided in a zenodo repository. For LULUCF emissions, we used data from the spatially explicit Bookkeeping of Land Use Emission (BLUE) model by Hansis et al.[43] used in Schwingshackl et al.[102]. The raw data can be found in the zenodo respository under: *Files/LUC_Blue_Data_for_REX.csv*. The additional GHG extension in REX3 can be combined with the REX3 database to calculate GHG emissions (including LULUCF) embodied in global supply chains for 189 countries and 163 sectors (1995 to 2022). All data are shared via a Creative Commons Attribution 4.0 International License. While EXIOBASE v.3.8.2 was used for this study, the REX3 database shared in the Zenodo repository is based on EXIOBASE v.3.8, as this is the earliest EXIOBASE version that can still be shared via a Creative Commons Attribution 4.0 International License.

## Code availability

The zenodo repository also includes the MATLAB code to calculate all results. The file *Integrate_Blue_into_REX3.m* includes the code to integrate the LULUCF data from the BLUE model, which are stored under the folder *Files/LUC_Blue_Data_for_REX.csv*. The code *Impact_coeff_emission_source.m* calculates the impact coefficients for the different emission sources and uses the price vector from the folder *Files/price_final_REX.mat* as input. The file *SCIM_calculations_6D.m* calculates the 6D impact array, while the file *Compile_data_for_sankeys.m* compiles the data for the Sankey, and the file *Compile_data_for_tableau_6D.m* compiles data for tableau to create the interactive tool. The codes rely on the REX3 database.

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## Author contributions
L.C. designed the research, compiled the database, calculated, visualized and interpreted the results, and wrote the manuscript. C.S. provided the LULUCF data from the BLUE model, interpreted the results, and contributed to manuscript writing. S.P. and S.H. designed the research, interpreted the results, and contributed to manuscript writing.

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